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Heavy Vehicle Performance on Grade and Climbing Lane Criteria

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Author(s): A. M. Khan, Principal Investigator; J. Y. Wong, Investigator and M. Rastogi, Reasearch Assistant - Carleton University

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Contact Person: Ataur Bacchus, Project Manager, Highway Innovations and Strategic Research Office (416) 235-4673;
Alex Ugge, Pavements and Roadway Office (416) 235-4698

Abstract: The objectives of this study were: (a) to assess the estimates of heavy vehicle performance on grade in existing MTO and other speed-distance curves; (b) to develop metric speed distance curves; and (c) to review MTO warrants for climbing lanes based on realistic speed-distance performance and on cost-effectiveness.

Weight/power information was compiled for a representative set of heavy vehicles. Two simulation models were developed to obtain speed-distance curves. Model I simulates vehicle motion in detail. Model II is less detailed and is based on empirical functions recommended by the American Society of Automotive Engineers. The results of the two models were consistent with each other and with field data.

Climbing lane warrants were reviewed and recommendations made, based on speed loss on grade, a drop in the level of service and cost-effectiveness.

The use of speed-distance curves and warrants is illustrated.

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Heavy Vehicle Performance on Grade and Climbing Lane Criteria

A. M. Khan
Principal Investigator

J. Y. Wong
Investigator

M. Rastogi
Research Assistant

Carleton University

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The Editor, Technical Publications
Room 320, Central Building
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Table of Contents

Acknowledgements vi

Executive Summary vii

1/ Introduction 1

1.1/ Background 1

1.2/ Study Objectives and Scope 2

1.3/ Report Organization 3

2/ Research Framework 4

2.1/ Research Approach 4

2.2/ Performance Parameters 6

2.2.1/ Weight - to - Power Ratio 6

2.2.2/ Basic Performance Parameters and Dimensions of Representative Vehicles 9

2.3/ Existing Speed-Distance Curves 12

2.4/ Methodology for the Development of Speed-Distance Curves 13

2.5/ Detailed Review of Speed-Distance Curves 13

2.5.1/ Field Data, Comparison with Model Output 13

2.5.2/ Review of Speed Distance Curves 13

2.6/ Review of Warrants 14

3/ Model I: Detailed Simulation of Truck and Recreational Vehicle Performance on Grade 15

3.1/ Model Structure 15

3.2/ Computer Simulation 17

3.3/ Main Features of the Computer Simulation Program 32

3.4/ Gear Change Delay 33

3.5/ Recreational Vehicle 33

4/ Model II: Simulation Model Based on SAE Truck Ability Prediction Procedure 34

4.1/ Basic Features 34

4.2/ Vehicle Speed and Net Tractive Force (Module I) 34

4.3/ Polynomial Curve Fitting (Module II) 38

4.4/ External Opposing Forces to Vehicle Motion (Module 3) 39

4.5/ Vehicle Acceleration (Module 4) 40

4.6/ Vehicle Deceleration (Module 5) 40

4.6/ Input Data for the Two Models 40

Table of Contents (continued)

5/ Heavy Vehicle Performance on Grade: Discussion of Model Output and Comparisons with Field Data. 41

5.1/ Introduction 41

5.2/ Interpretation of Model Output 41

5.3/ Basis for Comparison 41

5.4/ Comparison of Model Output 43

5.5/ Comparison of Model Output and Field Data 45

6/ Review of Climbing Lane Warrants 54

6.1/ Climbing Lane Decision 54

6.2/ Current Warrants for Climbing Lanes 56

6.2.1/ Ministry of Transportation, Ontario Warrants 56

6.2.2/ RTAC Guidelines 59

6.2.3/ AASHTO Warrants 60

6.2.4/ Transportation Research Board Guidelines 60

6.3/ Design Guidelines 61

6.4/ Example Applications of Warrants 62

6.5/ Cost-effectiveness Considerations 68

6.6/ Recommended Practice and Future Research 71

7/ Conclusions and Recommendations 73

7.1/ Conclusions 73

7.2/ Recommendations 75

References 77

List of Tables and Figures

Tables

2.1/ Truck Weight - to - Power Ratio 7

2.2/ Estimates of Weight - Out and Cube - Out 8

4.1/ Comparison of Modelling Approaches 36

5.1/ Comparison of Vehicle Performance Estimated by Various Models: Selected Vehicles, Crawl Speed, km/h 44

5.2/ Sites for Speed Studies 45

5.3/ Field Data: Truck and RV Speed -- km/h 46

5.4/ Speed Data (km/h): Automobile 47

5.5/ Field Data and Comparison With Model Output 48

5.6/ Comparison of Model Results and U.S. Field Data 50

6.1/ Comparison of Warrants and Recommended Practice 59

6.2/ Upgrade Level of Service and Operating Speed Without Truck Climbing Lane 66

6.3/ Application of Warrants: Sections 1 and 2, DHV = 300 67

Figures

2.1/ Methodological Framework 5

2.2/ A Histogram of Vehicle Gross Weight 8

2.3/ Trends in Weight - to - Power Ratio Since 1949 10

3.1/ The Basic Model of Vehicle Performance 16

3.2/ Flow Chart for the Simulation of Truck Speed-Distance Curves 18

3.3/ Computer Simulation Process 19

3.4/ Envelope for Engine Tractive Effort 23

3.5/ Schematic Diagram for Straight Truck/Recreational Vehicle 25

3.6/ Schematic Diagram for Semi-Trailer/Double-Trailer 28

3.7/ Case of Truck Acceleration and Deccelaration 31

4.1/ Computer Simulation Model based on the Truck Ability Prediction Procedure Recommended by SAE 35

5.1/ Comparison of Model II Output and Ministry of Transportation, Field Data, 5% Upgrade 51

5.2/ Comparison of Model II Output and Ministry of Transportation, Tractor-Trailer Test Data, 5% Upgrade 52

5.3/ Comparison of Model II Output and Field Data, (Site 3), 3.5% Upgrade 53

6.1/ Accident Involvement Rate of Trucks on Two-Lane Roads 55

6.2/ Critical Length of Grade, 120 kg/kw Truck 57

List of Tables and Figures (continued)

6.3/ Critical Length of Grade, 180 kg/kw Truck 58
6.4/ Cost-effectiveness of Climbing Lanes 69
6.5/ Economic Efficiency of Climbing Lanes 70

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The opinions expressed are those of the authors. They do not necessarily reflect the views of MTO or of Carleton University.

EXECUTIVE SUMMARY

Heavy vehicles in general and heavy trucks in particular, when travelling on grade, impede traffic and are known to increase accident rates on two lane rural highways. Climbing lanes have been used to improve traffic flow and safety on two lane highways. In conjunction with passing lanes, climbing lanes provide relief from platooning and enhance opportunities to pass slow moving vehicles safely.

Warrants for the provision of climbing lanes on two lane rural highways have been defined by a number of agencies, including the Ministry of Transportation, Ontario (MTO). Although such warrants exhibit similarities, there are differences as well. For design of climbing lanes and for checking the fulfilment of warrants, reliable heavy vehicle speed-distance curves are essential. Also, given that over time, characteristics of vehicles have changed, it is appropriate to update such information.

The objectives of this research were:

. to evaluate existing MTO and other truck speed distance curves,
. to develop realistic metric speed-distance curves that reflect characteristics of existing and forthcoming heavy vehicles, and
. to review warrants for climbing lanes, based on the principles of cost-effectiveness and realistic heavy vehicle speed-distance performance on grade.

At the outset, representative heavy vehicles were defined. It was decided to consider closed van straight trucks, semi-trailers and double-trailers. The recreational vehicle selected for investigation was an intermediate size passenger vehicle towing a closed-van trailer. Information was acquired on power and weight characteristics of freight vehicles from published sources, manufacturers/dealers and a limited survey of trucking companies. Recreational vehicle information was obtained from published sources and dealers. In order to cover a wide range of loading levels, the following weight-to-power ratios were selected for simulation of vehicle performance on grade:

. All types of trucks: 60, 120, 180, and 210 kg/kw
. Recreational vehicles: 40 kg/kw.

In the absence of any readily available methodology for developing speed-distance curves for given vehicle characteristics, two models were developed to estimate the

performance of vehicles (i.e., trucks and recreational vehicles).

Model I supports a detailed simulation of vehicle performance, based on the fundamental principles of vehicle mechanics and dynamics. Forces resisting vehicle motion and the tractive effort of the vehicle are incorporated explicitly. This model is detailed enough to differentiate among various types of heavy vehicles (i.e., straight truck, semi-trailer, double trailer, and recreational vehicle).

Due to the complexity of the model and the absence of refined information on the various coefficients and factors included, it is used in this study for checking the output of the second model. However, it could serve as a basis for the development of refined speed-distance curves.

Model II is based on the Truck Ability Prediction Procedure recommended by the Society of Automotive Engineers (SAE) and submitted for recognition as American National Standard. This model is more aggregate than Model I and cannot differentiate among various types of trucks.

Field studies were initiated to obtain data that could be used to test the model's output. In order to supplement field data collected as a part of this study, other truck speed-distance data obtained from MTO and U.S. FHWA were used to validate the model output.

The speed-distance curves obtained from models I and II are reviewed by comparing speed reduction of road vehicles for various grades and distances. In general, the truck speed-distance curves obtained from models I and II compare well with each other as well as with field data. Model II output is recommended for use in planning and design, and Model I output is suggested for research. Model II output is recommended because it is based on the SAE recommended practice for estimating truck performance.

The speed-distance curves contained in highway capacity seminar notes prepared for MTO correspond to a vehicle of weight/power ratio of 200 kg/kw, which is considered to be very heavily loaded. The use of a design vehicle represented by this level of loading would result in underestimation of truck speeds on Ontario two lane highways. It is recommended that the 180 kg/kw truck should be used as the typical heavy truck representing the 12.5th percentile truck speed and that a 120 kg/kw truck should be regarded as the average truck (corresponding to about the 50th percentile speed of trucks).

The speed-distance curves obtained from models for the recreational vehicle suggest a higher level of performance than estimated from field survey data for low grades of up to 3 to 4 percent. Such observations have also been made by previous researchers. Driver behaviour (not using engine power to the extent that is assumed by the models) may explain the disparity. However, the outputs of Models I and II correspond very well with those of other researchers' models.

Speed-distance curves for a variety of entry speeds and truck loading levels were developed and are included in the report for the use of planners, designers and researchers. In the case of heavily loaded trucks, some desired speeds are not attainable even at zero grade. For example, a truck with 180 kg/kw (regarded as the typical heavy freight vehicle) cannot attain 100 km/h speed on level road. Depending upon the region, and predominant commodities moved by truck, the planner has the option to choose the loading level (i.e., the weight-to-power ratio) and the entry speed that are believed to be realistic for that part of the highway network.

This report contains almost all relevant combinations of entry speed and weight/power ratios that may be used in climbing lane planning and design, and others can be inferred from the outputs included herein. On roads where truck traffic is significant, critical length of grade is to be based on truck performance on grade. The recreational vehicle curves are to be used when such vehicles represent the majority of slow moving traffic.

A review of climbing lane warrants suggests that the MTO warrant of heavy vehicle speed drop of 15 km/h is consistent with safety and service quality considerations. Warrants of other agencies reviewed follow this practice. It is recommended that in Ontario, climbing lanes should be considered on routes with sufficient volume of traffic, at those locations where the length of grade causes loaded vehicles to reduce speed 15 km/h or more below the entry or prevailing highway speed. Climbing lanes at such locations would avoid platooning and unreasonable delays. The accident rate for trucks on two lane roads suggests that the accident rate rises faster with speed differential when the latter is above 15 km/h speed differential.

It is also recommended that MTO continue to use the level of service or volume warrant. That is, should the level of service upgrade drop one level below that of entry level of service (e.g., level of service C on grade vs. B at the approach to the grade), a climbing lane should be considered.

A third criterion is recommended in addition to truck speed differential and a drop in level of service. It is the economic criterion of ensuring that in relative terms, an alternative with a higher estimated cost-effectiveness should be given preference in implementation. This criterion is currently used informally by most agencies, including MTO.

It is recommended that MTO continue the design practice of starting one climbing lane where the heavy vehicle speed drops 15 km/h below the prevailing highway speed, and ending it at the point where the heavy vehicle speed comes within 15 km/h of the speed of other vehicles. The practice of setting the minimum length of a climbing lane equal to 1.5 km should be maintained.

The use of speed-distance curves and warrants is illustrated in the report. The concept of the cost-effectiveness of climbing lanes as an aid to decision making is advanced and recommendations are made for the development of a cost-effectiveness model for the evaluation of climbing lane alternatives, to be implemented as a user-friendly microcomputer program.

Chapter 1

INTRODUCTION

1.1 Background

Heavy vehicles in general and heavy trucks in particular cause queues on grades due to their "gradability". In severe terrain or on isolated upgrades of significant length, crawl speeds of trucks, particularly on two lane highways, result in adverse effects on the quality of flow experienced by vehicles following trucks, reduction of service flow rates, and restrictions on the opportunities to pass slow moving vehicles safely. Climbing and passing lanes provide relief. Ultimately, twinning of extended sections of two lane highways could also be considered. In all these cases, it is essential that design and investment decisions be based on realistic truck and other traffic performance information as well as methodology for assessing cost-effectiveness of design options.

Planning and design guides and policy manuals used in Canada contain heavy vehicle performance information that is believed to be outdated. Furthermore, there is a need for improved procedures that would guide climbing lane planning and design decisions. The decision to provide climbing lanes and design features such as their location and length require the use of heavy vehicle and recreational vehicle speed-distance functions (curves). The curves contained in the Ministry of Transportation, Ontario (MTO) design manual date back to the 1960s [1]. In the late 1970s, as part of a highway capacity seminar, relatively newer truck speed-distance curves were introduced. However, these curves suggest the use of a design vehicle of weight-to-power ratio of 200 kg/kw (329 lb/hp) [2]. The geometric design manual published by the Roads and Transportation Association of Canada (RTAC) contains similar or identical curves [3].

The 1984 design policy manual of the American Association of State Highway and Transportation Officials (AASHTO) and the 1985 Highway Capacity Manual of the Transportation Research Board (TRB) contain truck speed-distance curves that reflect lower weight-to-power ratios [4,5]. The curves contained in the AASHTO Manual were developed by a computer simulation modelling study sponsored by the National Cooperative Highway Research Program (NCHRP) (U.S.A.) [6]. The TRB's Highway Capacity Manual Committee relied on this source as well, although curves were updated for a variety of vehicles and weight-to-power levels.

Since the publication of the Highway Capacity Manual in 1985, research studies have been initiated in the U.S.A. in order to further the knowledge of truck performance on two lane as well as multilane highways [7]. Although the information base on truck characteristics has improved in recent years, little new modelling work has been carried out to update curves on heavy vehicle performance upgrade [8,9,10].

In addition to knowledge gaps in the performance of heavy vehicles on grade, there is much confusion about warrants for the provision of climbing and passing lanes. Warrants for the provision of climbing lanes on multilane highways are at best loosely defined by transportation agencies. In the case of two lane highways, guidelines used by various agencies differ considerably.

The need for improved information is critical, given that truck fleet characteristics have changed over time and further changes are likely to arise from liberalized weights and dimensions regulations. Also, there is pressure to refine the knowledge base, criteria for the provision of climbing lanes, and methodology for the design and evaluation of alternatives owing to the need to improve the cost-effectiveness of highway infrastructure investments.

1.2 Study Objectives and Scope

The objectives of this research are:

1. to evaluate existing MTO and other truck speed-distance curves,

2. to develop realistic metric speed-distance curves that reflect the characteristics of existing and forthcoming heavy vehicles that use or will be using Ontario highways, and

3. to review warrants for truck climbing lanes, based on realistic speed-distance curves and principles of cost-effectiveness.

This study focuses on the development and application of truck and recreational vehicle speed-distance curves. The warrants for truck climbing lanes are to be reviewed as well. While this study recognizes the importance of the economic criteria for providing truck climbing lanes and the related subject of the interrelationship between the truck climbing performance and overall traffic stream characteristics, it is not the intent here to investigate the overall performance of two lane roads.

1.3 Report Organization

Chapter 2 covers the overall research framework. Representative vehicle characteristics, and the rationale for updating and validating heavy vehicle performance curves are discussed.

Chapter 3 describes a detailed simulation approach to the study of truck performance. Chapter 4 describes a second approach to truck performance prediction based on the procedure recommended by the Society of Automotive Engineers. Chapter 5 reports the analysis of the model output and its comparison with field data as well as speed-distance curves published by other agencies.

In Chapter 6, warrants for the provision of truck climbing lane are reviewed and the concept of cost-effectiveness of warrants is discussed. Chapter 7 presents conclusions and recommendations. Appendix A contains inputs and outputs of Model I (i.e., the detailed simulation model). Appendix B presents the inputs and outputs of Model II (based on the SAE recommended practice).

Chapter 2

RESEARCH FRAMEWORK

2.1 Research Approach

In assessing the need for, and establishing the design features of, climbing lanes, the concept of "critical length of grade" is used. A maximum length of a designated grade is required on which a selected design vehicle is able to operate without reducing its speed to an unreasonably low level. The specification of the entrance speed at the bottom of the grade depends upon the design speed as well as the posted maximum speed of the highway. The speed differential and the minimum speed of heavy vehicles on the grade below which platooning of the following vehicles occurs, and unsafe passing manoeuvers increase, are an important factor in the justification of climbing lanes.

The development of curves that represent heavy vehicle travel on grade and the use of these curves for establishing critical length of grade, require information on the following factors:

- identification of the representative heavy vehicles, and
- the weight-to-power ratio and other characteristics of such vehicles.

The research approach in this project takes into account the need for information for the development of speed-distance curves and the review of warrants for the provision of climbing lanes.

Figure 2.1 presents the overall research framework that was followed in this study. At the outset, vehicle groups that are generally classified as slow moving were defined. These include recreational vehicles (RVs), straight trucks, semi-trailers, and double-trailers.

Design parameters were studied next. The variables included in the study were: engine power and performance, gross weight, loading level (load factor), transmission characteristics, dimensions and tires.

An initial review of existing speed-distance curves was carried out in order to learn about the methodology used for the development of various curves and assumptions made for their development. The generally decreasing weight-to-power ratio, the increasing percentage of combination vehicles for medium to long haul movement, and the changing use of the straight truck for

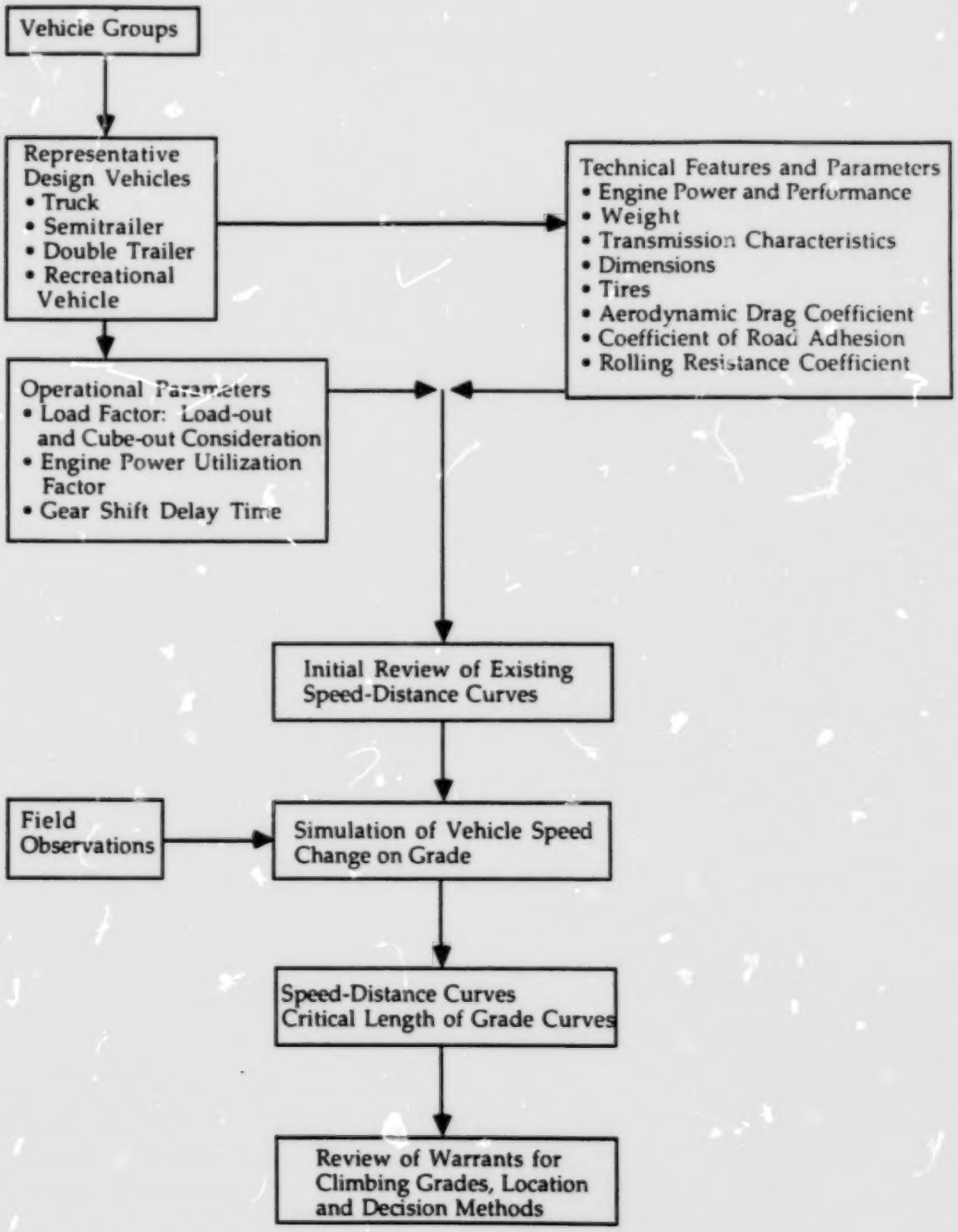

Figure 2.1: Methodological Framework

specialized short haul carriage of higher density cargo were noted.

The methodological requirements that were defined stressed the need to model trucks as well as slow moving recreational vehicles. Also, it was believed essential to develop techniques that allowed a wide variety of sensitivity tests on entry speeds and weight-to-power ratios.

Two models were developed for estimating speed distance curves. The first model is a detailed simulation of vehicle motion on grade. The second model is based on the Society of Automotive Engineers (SAE) recommended practice for the estimation of truck performance on grade [9,10].

For the development of the detailed simulation model, in addition to design parameters, operational parameters were included. These factors are noted in Figure 2.1.

The next step in the methodological framework was a field study carried out at three locations on Highway 17 and one location on Highway 417 in order to record speed characteristics of trucks, recreational vehicles and automobiles. These speed observations made at upgrade as well as down grade sections were used to verify results obtained from models.

Field observations made in this study as well as other field data collected by the MTO and by a number of agencies in the U.S.A. are used to assess the accuracy of the speed-distance curves obtained using the simulation models. For a variety of grades and distances, comparative studies are reported in Chapter 5. Detailed reviews of existing speed-distance curves are presented and merits of new curves obtained through this study are pointed out.

Warrants for climbing lanes were reviewed next and the current MTO practice noted. Two examples of the use of speed-distance curves are presented. The need to incorporate cost-effectiveness in the decision making process is highlighted and theoretical aspects of the incorporation of economic and performance factors are presented.

In the following sections of this chapter, selected methodological steps are described in greater detail.

2.2 Performance Parameters

2.2.1 Weight-to-Power Ratio

Gross weights of vehicles in Ontario have been published over the years in a variety of official documents. As a part of

weights and dimensions study coordinated by RTAC/CCMTA, a survey of Ontario truck weights and dimensions resulted in such data [8]. As a result of the recently announced weights and dimensions regulations for interprovincial transportation further information has become available [11]. In addition to gross weights that are permitted in Ontario without a special permit, overweight vehicles require special permits which are given for limited use only.

While the gross weight data are available, actual loading levels are difficult to obtain. For this purpose, a number of sources of information were investigated.

Three sources of information were used for obtaining weight-to-power ratios. Firstly, the MTO Project Manager and his colleagues obtained data by consulting the manufacturing industry and available in-house files. Secondly, a limited survey of truck power, weights and dimensions was initiated in order to obtain supplementary data. Thirdly, data published in Fleet Owner Manual Specs and Buyers' Directory were consulted [12]. Also, truck dealers provided some technical data.

From the above information sources, weight-to-power information was compiled (Table 2.1).

Table 2.1
Truck Weight-to-Power Ratio

Gross Weight (Kg.)	No. of Axles	Installed Horsepower (HP)	Weight/Power Ratio (Kg./Kilowatt)	Weight/Power Ratio (Lb./HP)
Heavy Wt.				
63,000	> 8	400-500	211.9-169.0	347-278
58,000	7 or 8	350-425	222.6-183.7	365-301
53,500	7 or 8	290-400	248.1-179.7	406-295
52,500	6	250-400	281.6-175.7	463-289
46,500	6	350-400	178.4-155.6	293-256
43,500	5			
42,000	5	250-350	225.3-160.9	370-264
39,000	5	300-315	174.3-118.0	286-193
Light Wt.				
26,200	<5	270-300	163.6-130.1	268-213

A histogram of gross vehicle weights for the Ontario truck population is shown in Figure 2.2.

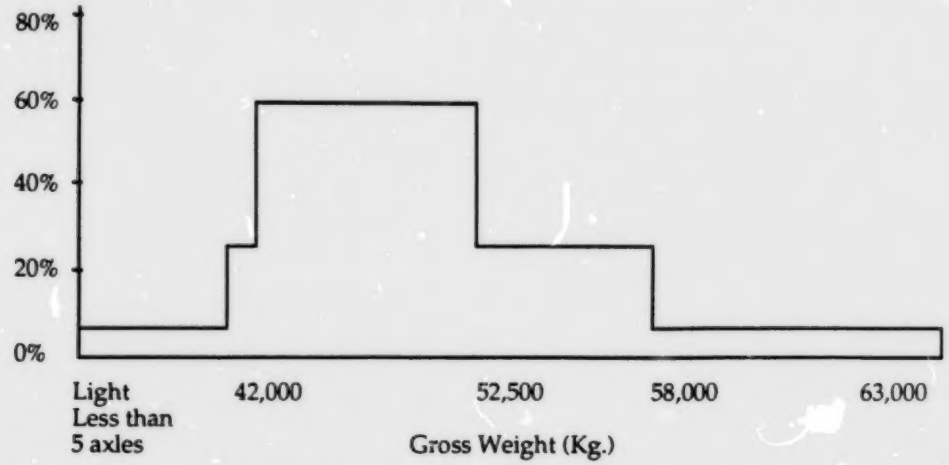

Figure 2.2: A Histogram of Vehicle Gross Weight

The extent of "cubic capacity used" and the extent of "utilization of allowable weight" by the trucking industry is difficult to establish. The estimates presented in Table 2.2 for the various types of services were obtained from a small number of responses from the industry. These estimates suggest a high level of utilization of cubic capacity as well as weight allowance by the industry. In relative terms, results indicate a higher level of cubic capacity utilization than the utilization of allowable weight.

Table 2.2
Estimates of Cubic Capacity and Allowable Weight Utilization
(Range of Responses)

Type of Service	% Cubic Capacity Used	% Allowable Weight Used
Truckload service	90 - 100	70 - 100
Less-than-truckload service (with consolidation at a terminal)	80 - 100	70 - 100
Other (specialized)	85	90 - 95

As is clear from data presented in this section of the report, the gross weight/rated power of trucks in Ontario could range from 118 kg/kw to 282 kg/kw, with the majority around 180 kg/kw. It should be noted that although in theory, weight/rated power could be higher than 180 kg/kw (e.g., 210 or higher kg/kw), such extremely heavy vehicles are not likely to attain maximum permissible speeds of 90 km/h or higher even at zero grade. Therefore, it is believed that weight/power ratio for most truck trips (other than empty truck trips) ranges from 120 to 180 kg/kw (200 to 300 lbs/hp).

Trends in weight/power ratio were examined by reviewing past and recent data and comparing the information obtained in this study to these data. Figure 2.3 records such observations. It appears that:

- over time, the weight/power ratio has fallen,
- it may be relatively stable now, or it may tend to rise somewhat in the future, due to liberalized weights and dimensions,
- the weight to power ratio increases as the allowable gross weight rises,
- for Ontario, the maximum theoretical weight/power ratio is slightly higher than 180 kg/kw and in practice, this ratio is likely to be 180 kg/kw or less due to cube out phenomenon.

The cumulative frequency distribution diagrams of wt/power ratio reported in the Highway Capacity Manual confirm the observation that almost 100% of trucks have weight/power ratio of 180 kg/kw or less. Also, the loading levels that can be represented by 120 kg/kw and 60 kg/kw correspond to average load and light load levels, respectively. Field data discussed in Chapter 5 confirm these initial observations.

2.2.2 Basic Performance Parameters and Dimensions of Representative Vehicles

An attempt was made to collect data on the following representative (design) vehicles: trucks, semitrailers, double trailers and recreational vehicles. Closed-van commercial vehicles were selected for simulation studies. The recreational vehicle chosen is a medium sized passenger car towing a closed van.

Basic performance parameter information was collected through published sources, namely past studies, the Fleet Owner Manual, and other literature such as papers published by the Society of Automotive Engineers (SAE). Also, manufacturers and dealers were contacted for the required data.

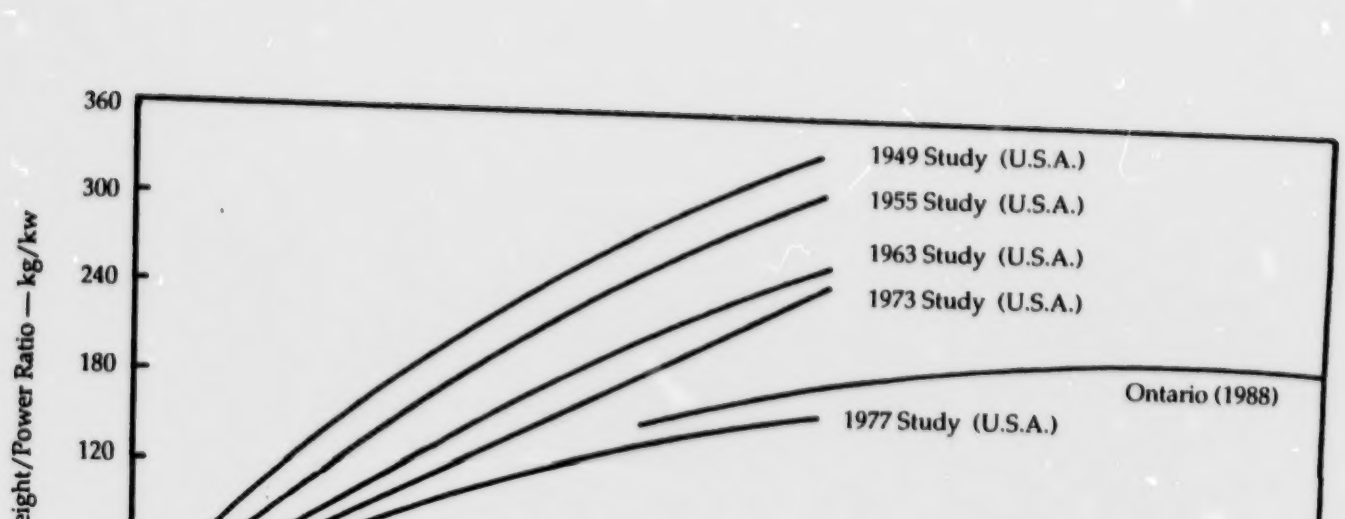

Figure 2.3: Trends in Weight-to-Power Ratio Since 1949
Source: FHWA (U.S.A.) and Ontario Data Contained in Table 2.1.

In the specification of truck characteristics, the carrier perspective was investigated. Factors that influence truck selection by carriers include:

. type of commodities carried and applications (i.e., dedicated loads, shared loads, etc.),
. type of roadway and topography,
. maximum speed desired for the vehicle,
. pick up and torque requirements, or grade ability preferred by the trucking company,
. region of operation -- service area, distribution networks,
. overall balance of speed, fuel efficiency, and operating cost desired by the operator, fleet owner or broker.

In order to achieve realistic simulation and analysis of truck performance, the following steps were taken:

. Acquiring engine performance data from manufacturers,
. Collection of truck data regarding power train combination (including engine, transmission and other relevant details),
. Defining actual permissible combinations for analysis,
. Obtaining information from recreational vehicle dealers on towing trailers (in terms of dimensions and weight capacity),
. Survey of passenger car dealers to ascertain typical type of car models used for recreational towing purpose,
. Data collection from tire manufacturers on dimensions and characteristics.

In the selection of truck characteristics for computer studies, it was realized that numerous specifications were possible. Realistically, the choice of vehicle characteristics depends upon the requirements of the purchaser of the vehicle and the availability of equipment. The probability of any two truck models (or assemblies) being identical is quite low. Experienced dealers were asked to identify the most typical combination of power-trains so as to establish representative models. This information was supplemental to the survey data.

For the final output of computer models, the following vehicles were selected with the recommended power train combinations:

. Truck simulations:
  - LTL-900 Ford Model (for 180 kg/kw, 210 kg/kw),
  - LN-8000 Ford Model (for 60 kg/kw and 120 kg/kw).
. Recreational Vehicle (RV): Hyundai Sonata 2351 CC displacement for towing a trailer.

It is believed that these vehicles are a realistic representation of gross vehicle weight limits in Ontario, and maximum gross vehicle weight rating (GVWR) of power units.

2.3 Existing Speed-Distance Curves

A preliminary review was carried out to obtain views on the existing speed-distance curves that are available to the transportation profession. The following were credited in the development of new curves, reflecting current trends and realistic operating conditions:

- MTO curves developed in the 1960s require updating since the assumptions used for their development are probably not valid at this time, and
- Current long combination vehicles and a change in vehicle characteristics provide a sufficient basis for revising the speed-distance curves.

Available background information on the AASHTO curves was reviewed. These curves, compared to those from field studies carried out in the U.S.A., appear to be conservative estimates of the performance of straight trucks and semi-trailers. Also, in the use of curves, there appears to be no recognition of the "cube-out" phenomenon. However, the Transportation Research Board's Highway Capacity Manual of 1985 overcomes this deficiency by providing three sets of curves, covering heavy, standard and light loading cases. However, such curves for the various categories of truck were not specified (i.e., curves for straight truck, semi-trailer, double).

The AASHTO and TRB curves were developed in the late 1970s through computer simulation. Assumptions underlying these should be re-examined because vehicle characteristics have changed (e.g., combination vehicles) and loading levels (i.e., weight/power ratios) have changed.

Available information on the Australian practice of characterizing truck performance was reviewed. While explicit data are not available, references have been found to several truck types, namely high powered 38t articulated vehicles, low powered 38t articulated vehicles, unloaded articulated vehicles, 4t trucks, 1t trucks and unloaded small trucks.

The investigators recognized that in the assessment of existing speed-distance curves as well as for the development of new curves:

- the effects of theoretical weight/power ratio and the "cube-out" phenomenon should be used as a basis to explain any differences between theoretical speed-distance characteristics and field observations, and
- performance variations within vehicle classes and between vehicle classes should be taken into account.

On the basis of the above considerations, it was agreed to produce a set of performance curves for given classes of vehicles, reflecting various loading levels.

2.4 Methodology for the Development of Speed-Distance Curves

Two models were developed for the study of truck performance on grade. Model I is a detailed simulation model of truck performance (Chapter 3). Model II (described in Chapter 4) utilizes the truck ability prediction procedure recommended by the SAE.

The detailed model can be used to simulate different categories of freight vehicles and the recreational vehicle. Various truck types are simulated for the following loading levels: heavy load (nearly 100% load factor or "weight-out" case -- 180 kg/kw), intermediate load (about 70% load factor or "cube-out" case -- 120 kg/kw) and light load (partially loaded, about 30% load factor, 60 kg/kw).

Model II is not able to differentiate different types of truck. Consequently, only a generic "truck" was simulated for various loading levels.

2.5 Detailed Review of Speed-Distance Curves

2.5.1 Field Data, Comparisons With Model Output

Field observations were carried out at four selected locations on Highways 17 and 417 in order to study truck and other vehicle speed drops on grades of known values. In order to supplement observations made as a part of this investigation, available data on truck speed on grade were obtained from MTO sources. Also, field data collected in the U.S.A. were acquired through published sources. In Chapter 5, data summaries as well as comparisons are reported.

The method used to collect speed data consisted of using radar meters to measure vehicle speed at the approach and upgrade. Distance was measured and data on highway profile were acquired from the MTO regional offices. In this research, due to budget constraints, truck weight/power ratio and load factor data could not be acquired from field studies. Statistical analyses and the use of field data in checking model results are reported in Chapter 5.

2.5.2 Review of Speed-Distance Curves

Existing as well as new curves obtained from the models were reviewed for relevance and accuracy. As for relevance, the use of appropriate representative vehicles and the approach speed were assessed. As for accuracy, field data were the main yardstick for

comparison. Also consistency among outputs of different models was believed to be a good indicator of accuracy. Results are noted in Chapter 5.

2.6 Review of Warrants

The last step in this study was the review of warrants (covered in Chapter 6). Various features of MTO warrants were assessed from the perspective of safety, level of service, and economics. Also, comparisons were made with warrants of other agencies. A number of recommendations contained in this report suggest a change in the choice of design vehicle, retaining a number of warrants that relate to safety and level of service, and the consideration of cost-effectiveness in evaluating climbing lane alternatives. Examples illustrating the use of speed-distance curves and warrants for climbing lanes are provided.

Chapter 3

MODEL I: DETAILED SIMULATION OF TRUCK AND RECREATIONAL VEHICLE PERFORMANCE ON GRADE

3.1 Model Structure

Performance characteristics of a vehicle represent its capability to accelerate, to decelerate and to negotiate grades. The tractive (or braking) effort and the resisting forces acting on the vehicle determine the performance potential of the vehicle. The tractive effort developed by the driven tires is generated by the engine torque through the transmission and is limited by the coefficient of road adhesion and the normal load on the driven tires. The major resisting forces acting on a road vehicle include:

1. aerodynamic drag,
2. rolling resistance of tires,
3. grade resistance, which might be favourable or unfavourable to vehicle motion depending upon whether downgrade or upgrade, and
4. resistance due to drawbar load (as in the case of recreational vehicle pulling a trailer).

The tractive effort, aerodynamic drag and rolling resistance are speed dependent as shown in Figure 3.1, while the grade resistance is a constant on a given grade. The notations shown in the figure are defined as follows:

ATF	available tractive force from the engine
E_0	equilibrium point, representing maximum attainable steady speed at which the vehicle can negotiate a given grade
$F_{net,a}$	net tractive force available for accelerating the vehicle
$F_{net,b}$	net force causing the vehicle to decelerate, when entering upgrade at speed V_2 higher than the maximum attainable steady speed of V_0, as shown in Figure 3.1
R_a	aerodynamic drag
ΣR_g	summation of all resisting forces including aerodynamic drag, rolling resistance, grade resistance, etc., at a given grade
Σ RO	resultant resisting force on a level grade
RR	rolling resistance
V_f	maximum speed at the level grade which can be attained by the vehicle, given no speed limit
V_{max}	maximum allowable highway speed on level grade

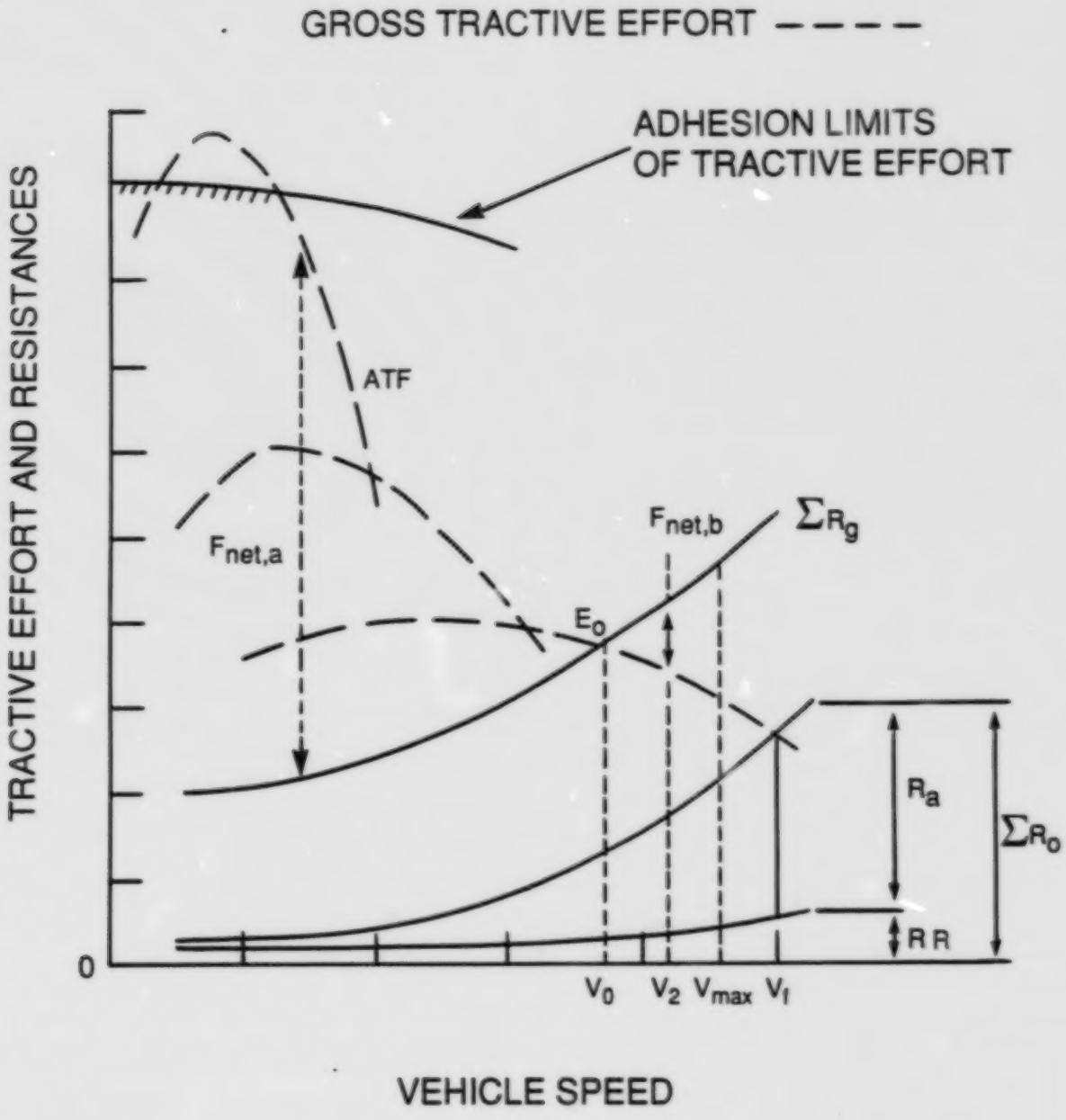

Figure 3.1: The Basic Model of Vehicle Performance

3.2 Computer Simulation

The objective of the program is to obtain the acceleration and deceleration curves (speed vs. distance) at different grades. It consists of several interconnected modules. The programming is done in a user-friendly manner.

The first module calculates the truck speed and available tractive force, given the basic characteristics of the engine (torque, speed) and the gear ratios as inputs. These values are then fitted into a polynomial allowing the truck speed and corresponding tractive effort to be determined at an interval of 0.1 km/h.

The second module calculates various resisting forces and the overall resistance for a given grade over the entire speed range.

The tractive force available at the driven wheels is limited by the nature of tire-road adhesion and the normal reaction to the driven tires. The maximum realizable tractive force is the lesser of the maximum tractive force determined by the engine and transmission characteristics and the maximum tractive force limited by the nature of the tire-road adhesion.

To take into account the effects of the inertia of the rotating parts on the vehicle acceleration characteristics, the module was formulated to include the calculation of the mass factor for the vehicle.

Figure 3.2 is a flowchart of the computer simulation process, and Figure 3.3 shows a detailed simulation process for Model I.

(i) Module 1: Calculation of Truck Speed and Engine Tractive Effort

The basic inputs for this module are the engine characteristics, in terms of engine speed (rpm) and engine torque (N-m). As many as 30 different data pairs can be read from the engine torque-engine speed curve (made available by the manufacturer) and for each set of values corresponding truck speed (km/h) and tractive force (N) are calculated. This is done for all the available gear ratios.

The key equations involved are presented below:

$$V = \frac{\sqrt{1 - (1 - 4A^2 K)}}{2AK} \qquad (1)$$

This value of V (truck speed) also takes care of the effect on speed due to tire growth factor.

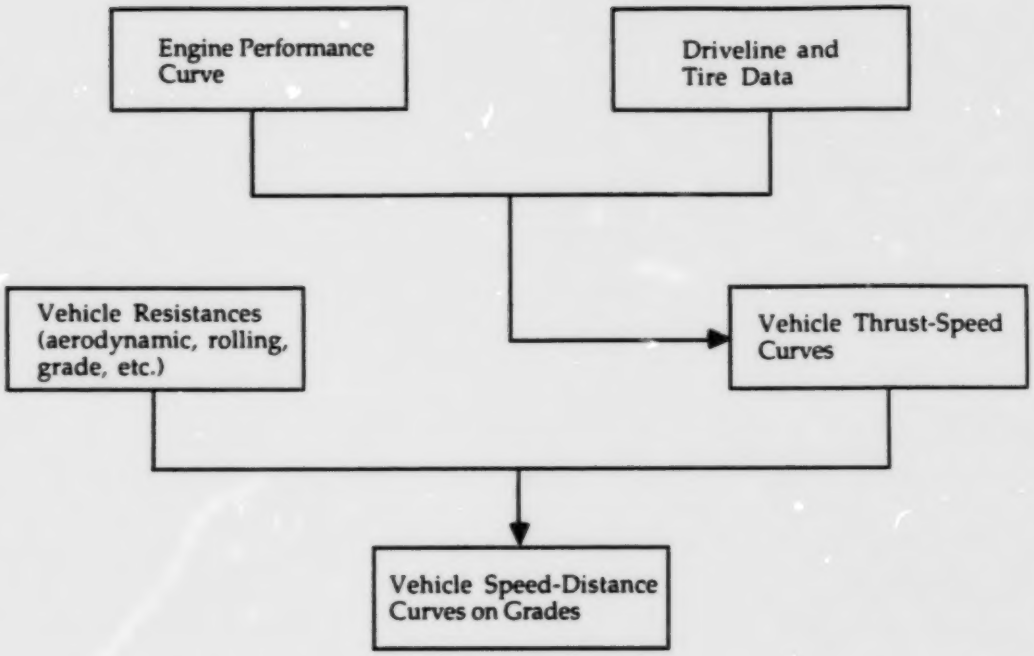
Engine Performance Curve
Driveline and Tire Data
Vehicle Resistances (aerodynamic, rolling, grade, etc.)
Vehicle Thrust-Speed Curves
Vehicle Speed-Distance Curves on Grades

Figure 3.2: Flow Chart for the Simulation of Truck Speed-Distance Curves

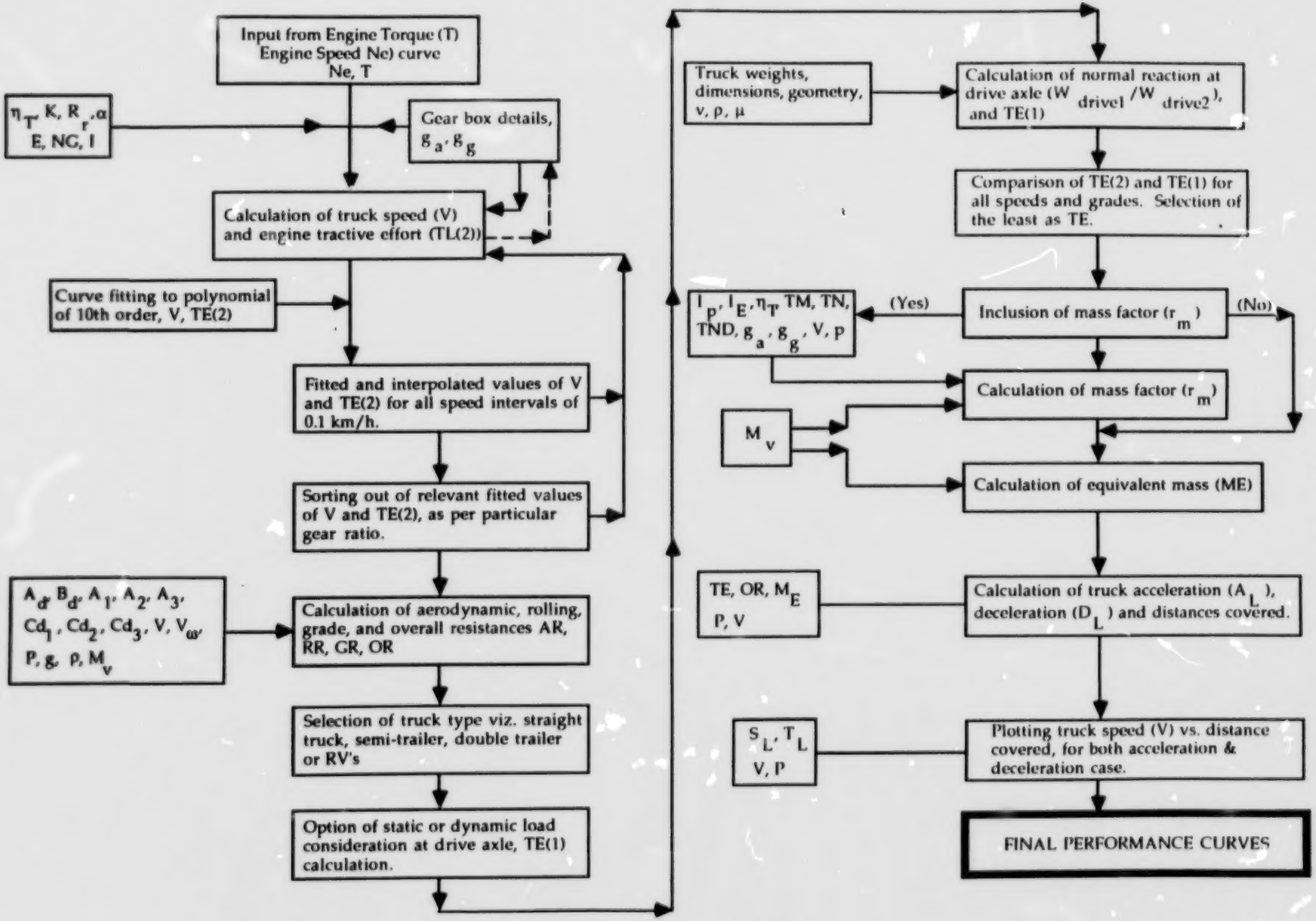
Input from Engine Torque (T) Engine Speed Ne) curve Ne, T
η_T, K, R_r, α E, NG, I
Gear box details, g_a, g_g
Calculation of truck speed (V) and engine tractive effort (TL(2))
Curve fitting to polynomial of 10th order, V, TE(2)
Fitted and interpolated values of V and TE(2) for all speed intervals of 0.1 km/h.
Sorting out of relevant fitted values of V and TE(2), as per particular gear ratio.
A_d, B_d, A_1, A_2, A_3, Cd_1, Cd_2, Cd_3, V, V_ω, P, g, ρ, M_v
Calculation of aerodynamic, rolling, grade, and overall resistances AR, RR, GR, OR
Selection of truck type viz. straight truck, semi-trailer, double trailer or RV's
Option of static or dynamic load consideration at drive axle, TE(1) calculation.
Truck weights, dimensions, geometry, v, ρ, μ
Calculation of normal reaction at drive axle (W_{drive1}/W_{drive2}), and TE(1)
Comparison of TE(2) and TE(1) for all speeds and grades. Selection of the least as TE.
I_P, I_E, η_T TM, TN, TND, g_a, g_g, V, P
(Yes)
Inclusion of mass factor (r_m)
(No)
Calculation of mass factor (r_m)
M_v
Calculation of equivalent mass (ME)
TE, OR, M_E P, V
Calculation of truck acceleration (A_L), deceleration (D_L) and distances covered.
S_L, T_L V, P
Plotting truck speed (V) vs. distance covered, for both acceleration & deceleration case.
FINAL PERFORMANCE CURVES

Figure 3.3: Computer Simulation Process (Model I)

η_T = .85 for first one third of gear ratios, starting from 1st gear
= .88 for next one third of gear ratios
= .93 for last one third of gear ratios (2)

These values are obtained from reference 15, page 140.

$$R_{rv} = R_r (1+KV^2) \quad (3)$$

$$TE(2)' = (T.C_2.\eta_T.\alpha)/R_{rv} \quad (4)$$

$$A_t = (1-1.312 \times 10^{-4}.E) \quad \text{(P.43, Ref.[2])} \quad (5)$$

$$TE(2) = TE(2)'.A_t \quad (6)$$

Where:

A	$3.C_1/25.C_2$
A_t	altitude factor for engine performance correction
C_1	Ne . Rr . π
C_2	$g_a \cdot g_g$
E	altitude above sea-level (m)
g_a	drive axle ratio
g_g	gear box ratio
K	tire growth factor
	0 (for radial ply tire)
	1.84×10^{-6} (for cross ply tire, for V in km/h)
N_e	engine speed (rpm)
R_r	static rolling radius of drive axle wheel (m)
R_{rv}	dynamic rolling radius of drive axle wheel (m)
T	engine torque (N-m)
TE(2)	tractive force available as per engine characteristics, with altitude correction (N)
TE(2)'	tractive force available as per engine characteristics, without altitude correction (N)
V	truck speed (km/h)
α	engine utilization factor (≤ 1)

η_T transmission efficiency

The K factor takes into account the effect of truck speed on the rolling radius of the wheel and the altitude factor allows us to compare performance of different engines under the same operating conditions, taking into account the change in atmospheric conditions, basically as a function of altitude above sea level.

From the calculations, V and TE(2) data pairs for each gear can be obtained, which are equal to the number of discrete input points for N_e and T. These V and TE(2) values serve as input for the next module.

(ii) Module 2: Polynomial Curve Fitting

The output of Module 1 serves as an input for Module 2. This module fits a polynomial to the discrete V and TE(2) data pairs for each gear.

The polynomial fitted is of the 10th order, which is sufficiently high for precise results (normally the curve fitted is of 6th degree).

This allows us to have the V and TE(2) values starting from V=0 km/h at the increments of 0.1 km/h, till the maximum speed that is allowed on the highway is reached. This is done for all the gears.

The data pairs appropriate to the operating range of each gear are taken for determining the speed-distance curves. Every gear, starting from the first gear, is utilized to its full extent and then the gear change takes place.

The final output of this module gives an envelope of tractive effort encompassing all the gears. This is taken as TE(2)-envelope. Depending upon the intersection of individual gear's tractive effort curve, the envelope might look as in Figure 3.4(a) or 3.4(b).

(iii) Module 3: Calculation of Resisting Forces

This module calculates all the resisting forces acting on the truck in motion. These are aerodynamic drag (AR), rolling resistance (RR) and resistance due to grade (RG).

The aerodynamic drag has been divided into component drags of tractor, semitrailer and double, by considering relevant drag area and drag coefficients for different units. Also the effect of wind speed is taken into account.

In the case of rolling resistance (RR), the dynamic rolling resistance coefficient is used to account for the increasing value of rolling resistance coefficient with increasing speed. Please note the following characteristics:

RR - varies with speed and normal load
AR - varies with speed but not with grade
GR - varies with grade but not with speed

Thus the total resistance (OR), which is equal to the summation of all resistances, changes with the speed as well as with the grade. The relevant equations used are noted below.

$$RR = (A_d + B_d\ V)\ .\ M_v\ .\ g \qquad (7)$$

$$AR_i = Z\ A_i\ C_{di}\ .\ 0.07716\ . \qquad (8)$$

$$AR = \sum_{i=1}^{n} AR_i \qquad (9)$$

$$GR = M_v\ .\ g\ .\ p\ .\ 10^{-2} \qquad (10)$$

$$OR = RR + AR + GR \qquad (11)$$

All these resistances are measured in Newton.

where:

A_d static rolling resistance coefficient
A_i respective frontal area for tractor, semitrailer and double trailer (m^2)
AR total aerodynamic drag (N)
B_d dynamic rolling resistance coefficient
Cd_i respective aerodynamic drag coefficient for tractor, semitrailer and double trailer
g gravitational constant (m/s^2)
GR grade resistance (N)
M_v gross mass of the truck (kg)
n represents the number of different truck units like tractor, semitrailer or double trailer
OR sum of all the opposing forces (N)
total rolling resistance (N)
RR total rolling resistance (N)
p percent grade (denoted as +p for upgrade and -p for downgrade)
V truck speed (km/h)
V_w wind speed (km/h)
Z $0.5\ \rho\ (V+V_w)^2$
ρ air density (kg/m^3)

These values of resistances are calculated for all speeds (0 to V_{max}) and for all grades -9% to +9%.

(iv) <u>Module 4: Calculation of Tractive Effort Available as per Nature of Road-Tire Adhesion</u>

This module calculates the available tractive force at the driven tires which is limited by the nature of road-tire

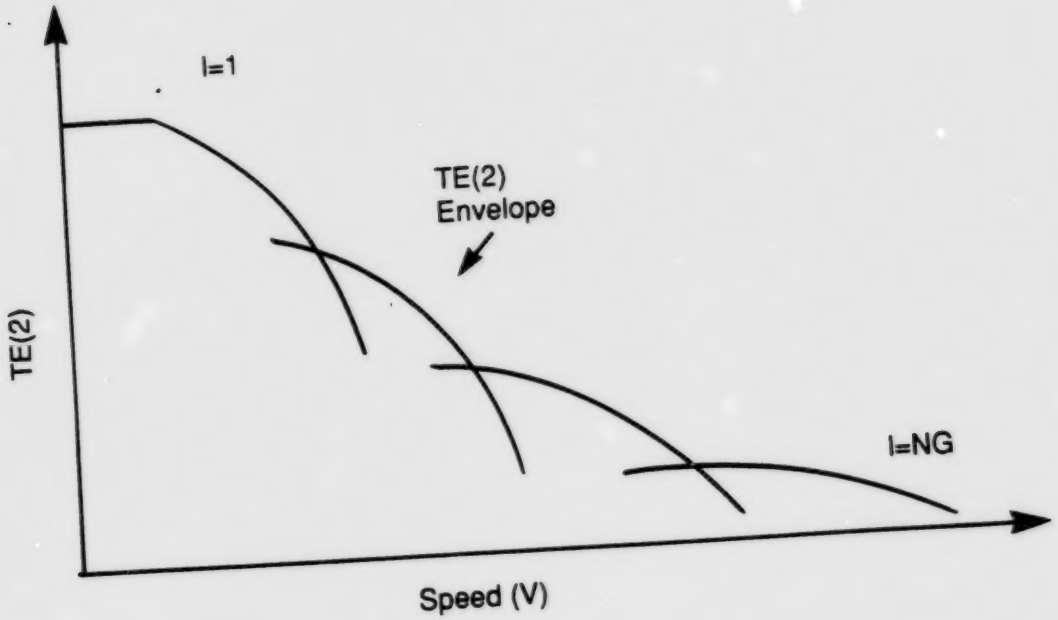

Figure 3.4 (a)

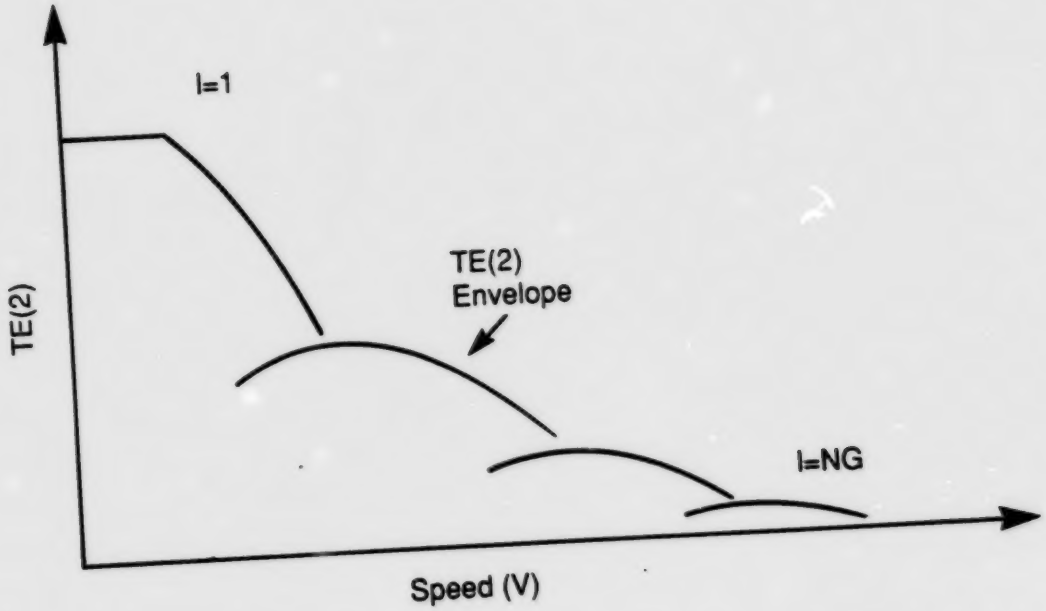

Figure 3.4 (b)

Figure 3.4: Envelope for Engine Tractive Effort

adhesion.

This tractive effort is termed as TE(1), and depends upon the normal reaction at the drive axle and coefficient of road-tire adhesion.

Two different submodules (sub-programs) have been written to calculate drive axle reactions. One deals with the case of straight trucks and recreational vehicles and the other with the case of semi-trailer and double. Each of these submodules has the option of considering either static load or dynamic load.

Dynamic load differs from the static loading in the respect that it takes into account the load on the drive axle due to vehicle motion. The vehicle acceleration is found by iteration for each speed at each grade.

Key equations used in determining dynamic load on the drive axle (or axles) are presented below.

(a) Dynamic Load-Straight Truck and Recreational Vehicle (Figure 3.5) (*)

$$W_{drive1} = (M_v \cdot g \cdot L_3 + AR_1 \cdot h_{a1} + M_v \cdot h_1 \cdot A_c + R_{d1}\, h_d + M_v \cdot h_1 \cdot P \cdot g \cdot 10^{-2})/L_1 \quad (12)$$

$$TE(1) = \mu W_{drive1} \quad (13)$$

where:

A_c truck acceleration (m/s^2)

AR_1 aerodynamic drag on truck/RV (N)

L_1 truck wheel-base (m)

L_3 distance between front axle and C.G. of the truck (m)

M_v gross mass of the truck (kg)

R_{d1} drawbar pull in case of recreational vehicle (N)

TE(1) tractive force available as per the nature of road-tire adhesion (N)

W_{drive1} normal reaction at drive axle (N)

μ coefficient of road-tire adhesion

* For a small angle (θ), cos θ tends to be unity. As such it is assumed to be unity in the forthcoming equations.

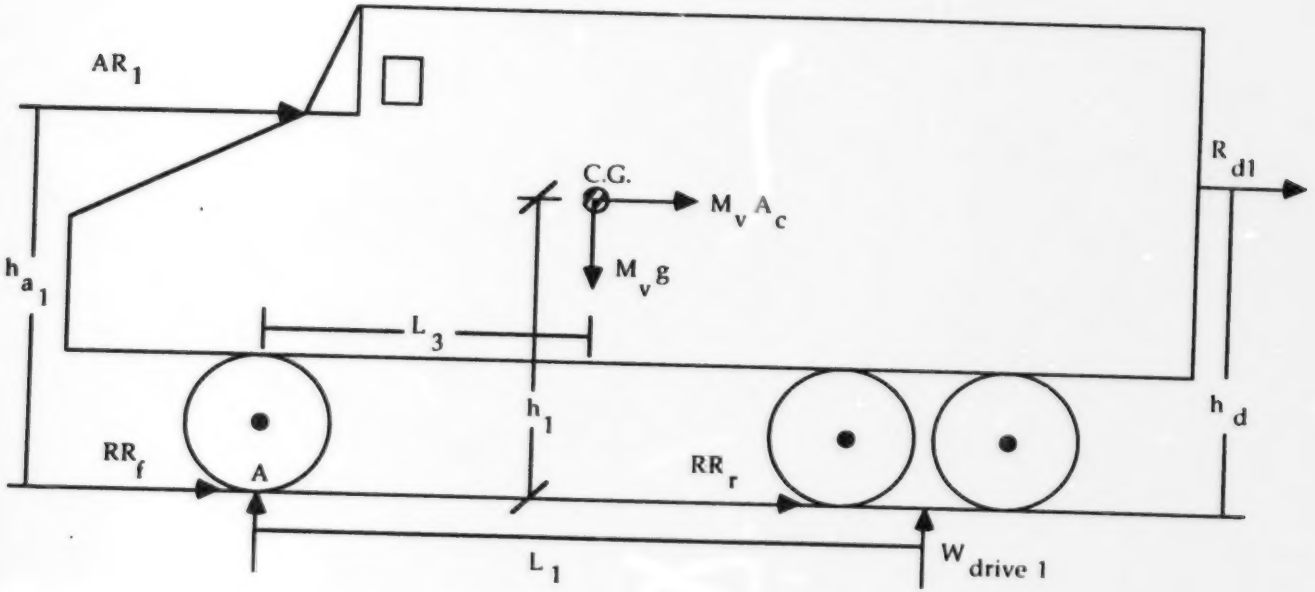

Figure 3.5: Schematic Diagram For Straight Truck/Recreational Vehicle

Other variables, e.g., h_1, h_d and h_{a1}, are as shown in Figure 3.5.

(b) Dynamic Load-Semi-trailer and Double Trailer (Figure 3.6)

$$W_{drive2} = (M_1 \cdot g \cdot L_3 + M_1 A_c \cdot h_1 + M_1 \cdot g \cdot p \cdot 10^{-2} \cdot h_1 + F_{hi} \cdot h_3 + AR_1 \cdot h_{a1} + (L_1 - d_1) Wh_i)/L_1 \quad (14)$$

$$TE(1) = \mathcal{M} W_{drive2} \quad (15)$$

where:

AR_1 aerodynamic drag on tractor (N)

d_1 distance between hitch and center of drive axle (m)

F_{hi} horizontal reaction at hitch due to semitrailer and/or doubletrailer (N)

L_1 tractor wheel-base (m)

L_3 distance between front axle and C.G. of the tractor (m)

M_1 mass of tractor (kg)

W_{drive2} normal reaction at drive axle (N)

W_{hi} vertical reaction at hitch due to semitrailer and or double trailer (N)

Also:

$$W_{hi} = M_2 . g - W_s \quad (16)$$

$$W_s = [M_2.(g.d_2 + A_c.(h_2-h_3) + g.p.10^{-2}.(h_2-h_3)) + AR_2.(ha_2-h_3) + R_d.(h_d-h_3)]/(L_2+X.h_3) \quad (17)$$

$$F_{hi} = M_2.(A_c+P.10^{-2}g) + AR_2+R_d+X.W_s \quad (18)$$

$$R_d = 0 \text{ (for semitrailer case)}$$

$$= AR_3 + M_3(g.P.10^{-2}+A_c+g.X) \text{ (for double-trailer)} \quad (19)$$

where:

AR_2 aerodynamic drag on the semitrailer (N)

AR_3 aerodynamic drag on the double trailer (N)

d_2 distance between semitrailer C.G. and hitch (m)

L_2 distance between hitch and rear axle (or at centre of group of rear axles) of semi-trailer (m)

M_2 mass of semitrailer (kg)

M_3 mass of double trailer (kg)

W_s normal reaction at rear axle (or at centre of group of rear axles of semi-trailer (N)

X $(A_d+B_d\ V)$

h_1, h_2, h_3, h_d, h_{a1}, h_{a2} are as shown in Figure 3.6.

Static Loading Case: In the case of static loading, the vehicle is considered to be stationary and forces due to vehicle motion are set to zero.

Static or Dynamic Loading?: The choice of static or dynamic loading in the calculation of TE(1) depends upon the level of precision, desired.

(v) Module 5: Comparison of Tractive Force (TE(1) and TE(2)) and Calculation of Equivalent Mass

In this module the comparison of tractive forces available at drive axle is made between TE(1) and TE(2) for all speed at all grades and the lesser of the two is selected as the final tractive force (TE) available for propulsion.

In the calculation of truck speed-distance curve, the rotating inertia of wheels and of components in the engine and driveline are taken into account, by introducing equivalent mass (ME) concept.

Mass factor (r_m) is introduced and equivalent mass (ME) of truck is then the product of truck mass and r_m (r_m is always >1).

Differentiation of r_m is also made depending on whether the final tractive force (TE) is governed by TE(1) or by TE(2).

Relationships for r_m are as given below.

If TE depends on TE(1)

$$r_m = \left[1 + \frac{(TN-TND)\,I_w}{M_v . R_{rv}^2}\right] \qquad (20)$$

$$ME = M_v \cdot r_m$$

If TE depends on TE(2)

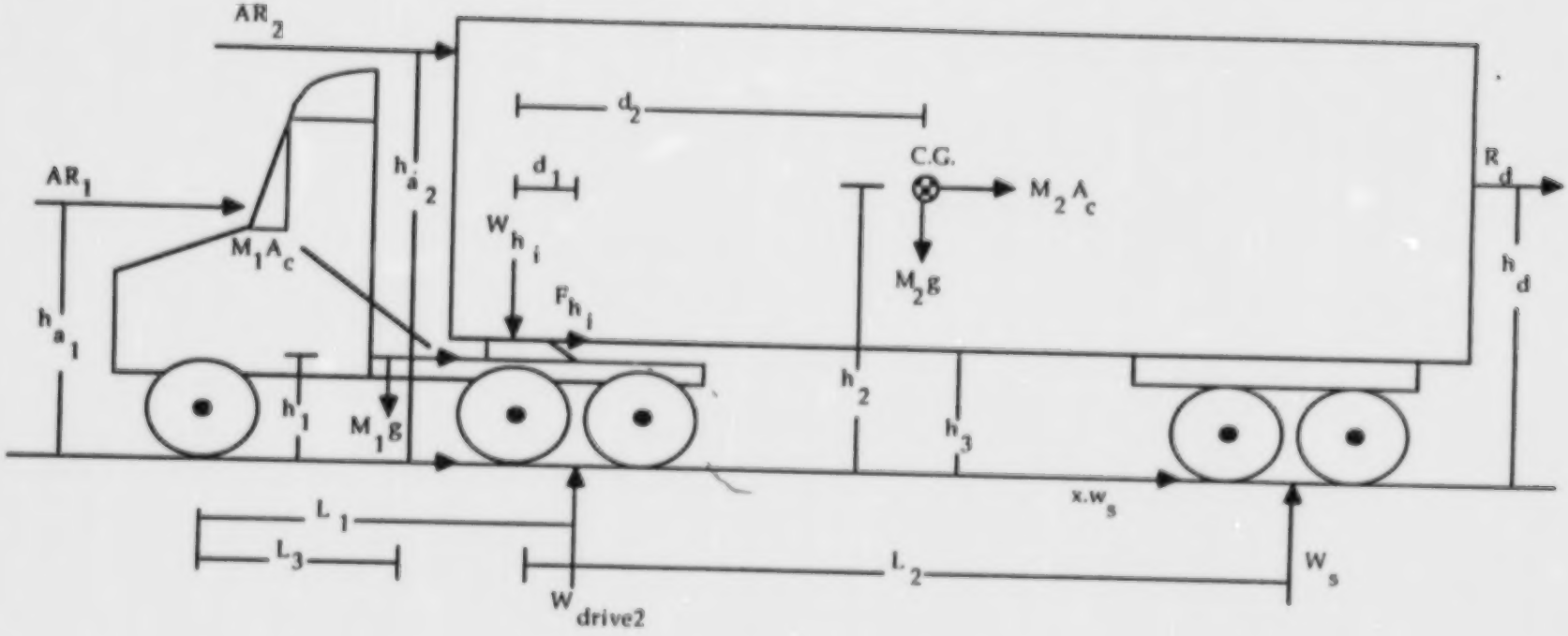

Figure 3.6: Schematic diagram for Semi-Trailer/Double-Trailer

$$r_m = \left[1 + \frac{TN \cdot I_w}{M_v \cdot R_{rv}^2} + \frac{\sum I_i G_i^2}{M_v R_{rv}^2}\right] \quad \text{(Ref.15, p.150)} \qquad (21)$$

and then

$$ME = M_v \cdot r_m \cdot$$

where:

G_i gear ratio with respect to driven wheel

I_i mass moment of inertia of the rotating components connected with the drive line having gear ratio G_i with respect to the driven wheel ($kg\text{-}m^2$)

I_w mass moment of inertia of each tire with rim ($kg\text{-}m^2$)

ME equivalent mass of vehicle (kg)

M_v gross mass of truck (kg)

R_{rv} dynamic rolling radius of drive-axle wheel (m)

r_m mass factor

TE tractive force available (N)

TN total number of wheels in truck assembly

TND total number of wheels in tractor/truck drive axle

The difference between two r_m's is that in the first case when TE(1) is less than that determined from the engine and driveline characteristics deal with the maximum transferable tractive force that the tire-road contact can support and are not concerned about drive line torque or inertia. The tractive force does not have to overcome the inertia of the engine which is assumed taken into account before TE(1) becomes available at ground. So the only factor which the tractive effort has to overcome is the translatory and small part of rotating inertia of the non-driven wheels. That is why equation (20) considers only (TN-TND) wheels, and also the inertia of the rotating parts of the engine is omitted. Thus, if TE depends on TE(1), equation (20) should be used.

The situation is not the same when TE is governed by TE(2). Here the tractive effort is reflected back to engine and the engine torque must now overcome both wheel inertia as well as engine and driveline inertia (equation (21)). Equation (21) should be used in this case.

Finally, there is an option of whether or not to include the mass-factor, depending upon whether it is negligible or not.

(vi) Module 6: Calculation of Truck Acceleration

Having obtained all the inputs required such as the tractive force available, resultant force opposing the motion and the equivalent mass, the truck acceleration and hence distance covered is calculated.

For the calculation of acceleration (starting at V=0 km/h), median values of all forces and equivalent mass at a speed interval ΔV is used (see Figure 3.7).

Therefore:

$$A_L = [(TE_j + TE_{j+1}) - (OR_j + OR_{j+1})]/(ME_j + ME_{j+1}) \quad (22)$$

$$S_L = 0.07716\ (V_{j+1}^2 - V_j^2)/(2.A_L) \quad (23)$$

where:

A_L acceleration up/downgrade (m/s^2)

j denotes the jth speed interval

ME_j equivalent mass of vehicle at j^{th} speed interval (N)

ME_{j+1} equivalent mass of vehicle at $j+1^{th}$ speed interval (N)

OR_j total opposing resistance at j^{th} speed interval (N)

OR_{j+1} total opposing resistance at $j+1^{th}$ speed interval (N)

S_L distance covered for the given speed interval (ΔV), during acceleration (m)

TE_j tractive force available at j^{th} speed interval (N)

TE_{j+1} tractive force available at $j+1^{th}$ speed interval (N)

V_{j+1} vehicle speed at $j+1^{th}$ speed interval (km/h)

V_j vehicle speed at j^{th} speed interval (km/h)

ΔV $V_{j+1}-V_j$ (km/h)

When A_L is less than or equal to 0.0001 m/s^2, the vehicle is assumed to operate at constant speed. Truck speed is plotted against cumulative distance travelled up/down the grade.

(vii) Module 7: Calculation of Truck Decceleration

Similarly, calculation of truck decceleration is carried out starting from V equal to V_{max}, i.e., the maximum allowable speed on highway at level grade (also taken as grade entering speed of the truck) towards equilibrium speed V_0. Deceleration is calculated until it becomes negligible, i.e., less than 0.0001

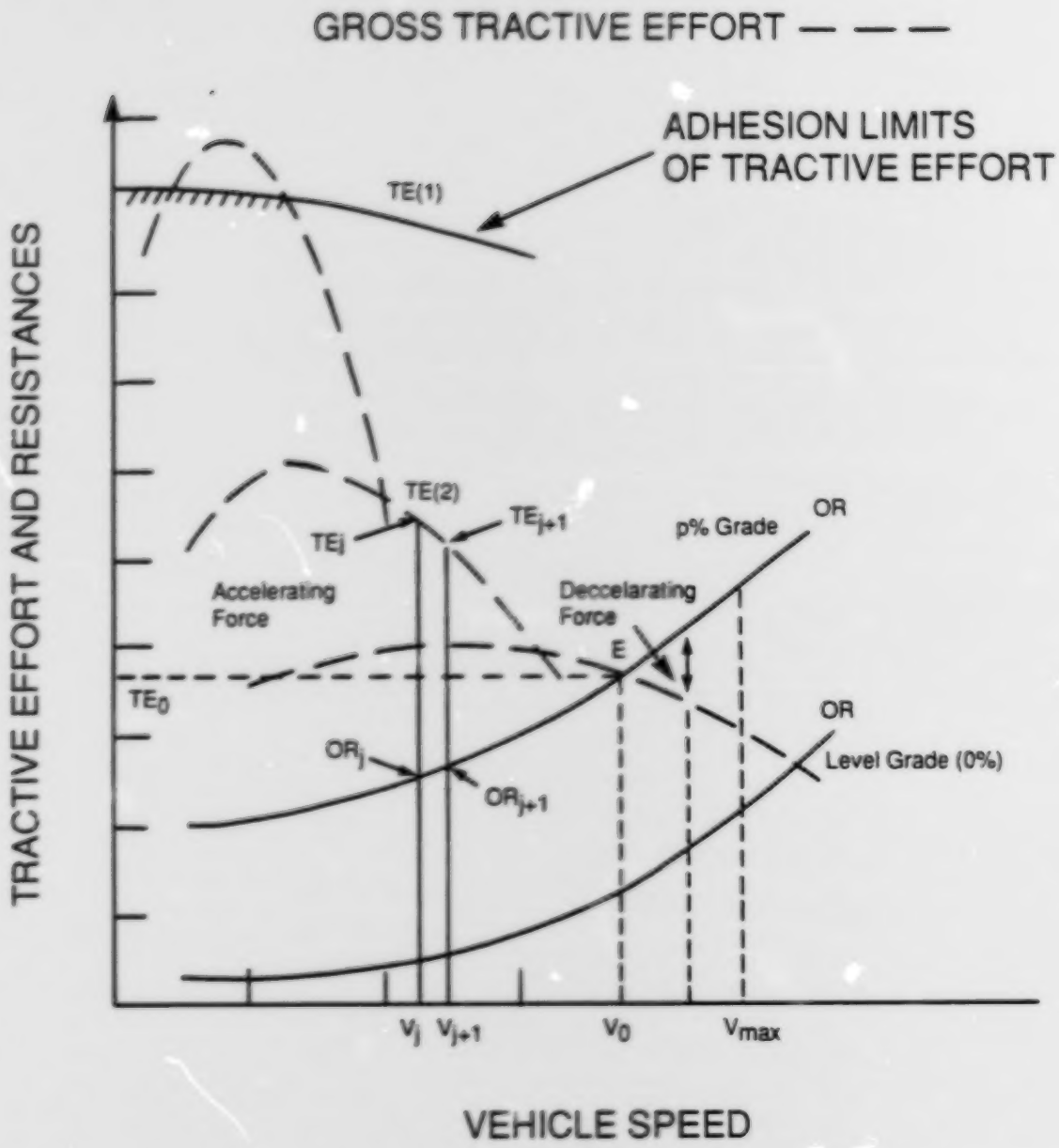

Figure 3.7: Case of Truck Accelaration and Deccelaration

m/s^2, and then constant speed is attained.

$$D_L = [(OR_j + OR_{j-1}) - (TE_j + TE_{j-1})]/(ME_j + ME_{j-1}) \quad (24)$$

$$T_L = \frac{(V_j^2 - V_{j-1}^2) \times 0.07716}{2 \cdot D_L} \quad (25)$$

where:

D_L deceleration upgrade (m/s^2)

T_L distance covered for given speed interval during deceleration (m)

V_{j-1} vehicle speed at $j-1^{th}$ speed interval (km/h)

Starting from V_{max} (i.e., allowable speed limit), truck speed is plotted against cumulative distance.

3.3: Main Features of the Computer Simulation Program

1. Tire growth factor is introduced to account for the change in rolling radius of wheels with truck speed (V). It is used in the formula called as 'Dunlop Formula' and is expressed as a function of V^2. It is a reasonable relationship since stresses due to centrifugal effect in a rotating body varies with V^2 [13].

2. Introduction of engine power utilization factor, α, enables us to take into account individual truck driver behaviour. It is a direct indication of the throttle opening of the engine, while the truck is in motion. It can differ from driver to driver, under otherwise identical circumstances.

3. For a better understanding of aerodynamic drag on the truck (tractor, semi and double trailer), the areas and drag coefficient are used separately for each unit. The effect of separation between tractor and semitrailer and between semitrailer and double on their respective drag coefficient is taken into account.

4. Instead of static rolling resistance coefficient dynamic rolling resistance coefficient has been used. It depends on the truck speed.

5. The case, where tractive force available at wheels may be limited by the nature of road-tire adhesion, is also considered. This may be significant for the light weight trucks and recreational vehicles.

6. While considering the tractive force limited by road-tire adhesion, options for using either static load or the dynamic load have been provided to suit the desired level of precision.

7. The simulation program takes care of the rotating inertia of the wheels of the truck, as well as that of the engine. All these considerations are reflected in the factor known as "mass factor" (r_m). The calculation of r_m depends upon whether the available tractive force at the driven wheels the driven is governed by engine torque driveline characteristics or by the road-tire adhesion. Depending upon the accuracy desired, r_m may or may not be used in the final calculations.

8. The overall simulation program treats straight truck, tractor-semitrailer, double-trailer or recreational vehicle, distinctly, and accounts for different axle and tire configuration.

9. The computer program is versatile and can be used for predicting performance characteristics of different types of on-road vehicle including cars, vans, etc.

3.4 Gear Change Delay

The simulation model can take into account the effect of the gear shift delay on vehicle performance. The use of the gear shift feature results in discontinuities in the speed-distance profile. In order to produce final curves for climbing lane planning and design, smoothing the computed results becomes necessary. Given the difficulty of simulating the gear shift behaviour of drivers, variations in engine transmission characteristics, and the small difference between smoothed curves and those obtained without the gear shift feature of the model (typically less than 1 km/h), it was decided not to use the gear shift feature. However, the gear shift delay feature of the model could be used for further research in modelling vehicle performance on grade.

Past researchers have either ignored the gear shift feature or reported average speeds that fall between the values obtained with and without gear shift delay [6].

3.5 Recreational Vehicle

The detailed simulation model can evaluate the performance of the representative recreational vehicle. The engine characteristics and design parameters of the representative recreational vehicle used and results are included in Appendix A.

Chapter 4

MODEL II: SIMULATION MODEL BASED ON SAE TRUCK ABILITY PREDICTION PROCEDURE

4.1 Basic Features

This simulation program, unlike Model I, is based on the truck ability prediction procedure recommended by the SAE [9,14]. The computer program consists of five modules. The various modules deal with:

- the calculation of the tractive effort and vehicle speed as determined by the engine and driveline characteristics,
- fitting these values on to a polynomial for obtaining continuous curves for tractive effort vs. speed,
- computation of overall motion resistance, and
- calculation of acceleration and deceleration of the vehicle on upgrade or downgrade.

The method and calculation procedure are described below. These are based on the guidelines provided by the SAE. A few modifications were made in order to use the model for the estimation of the performance of the recreational vehicle.

The structure of Model II is shown in Figure 4.1. It would be of interest to highlight the procedural differences between this model and the detailed simulation model covered in Chapter 3. Table 4.1 shows a comparison of the features of the two models.

Clearly, Model II (based on the SAE approach) is aggregate in nature. The lack of capability in a number of aspects listed in Table 4.1 should not be taken, however, as an indication that the SAE recommended practice is not adequate for predicting vehicle performance.

4.2 Vehicle Speed and Net Tractive Force (Module 1)

This program computes the speed of the vehicle (i.e., truck or RV) and net tractive force available after accounting for the chassis frictional losses. The slippage of the vehicle running gear is also accounted for and its value is on average taken as 3% for recreational vehicles. The available force is also corrected for engine performance at altitudes.

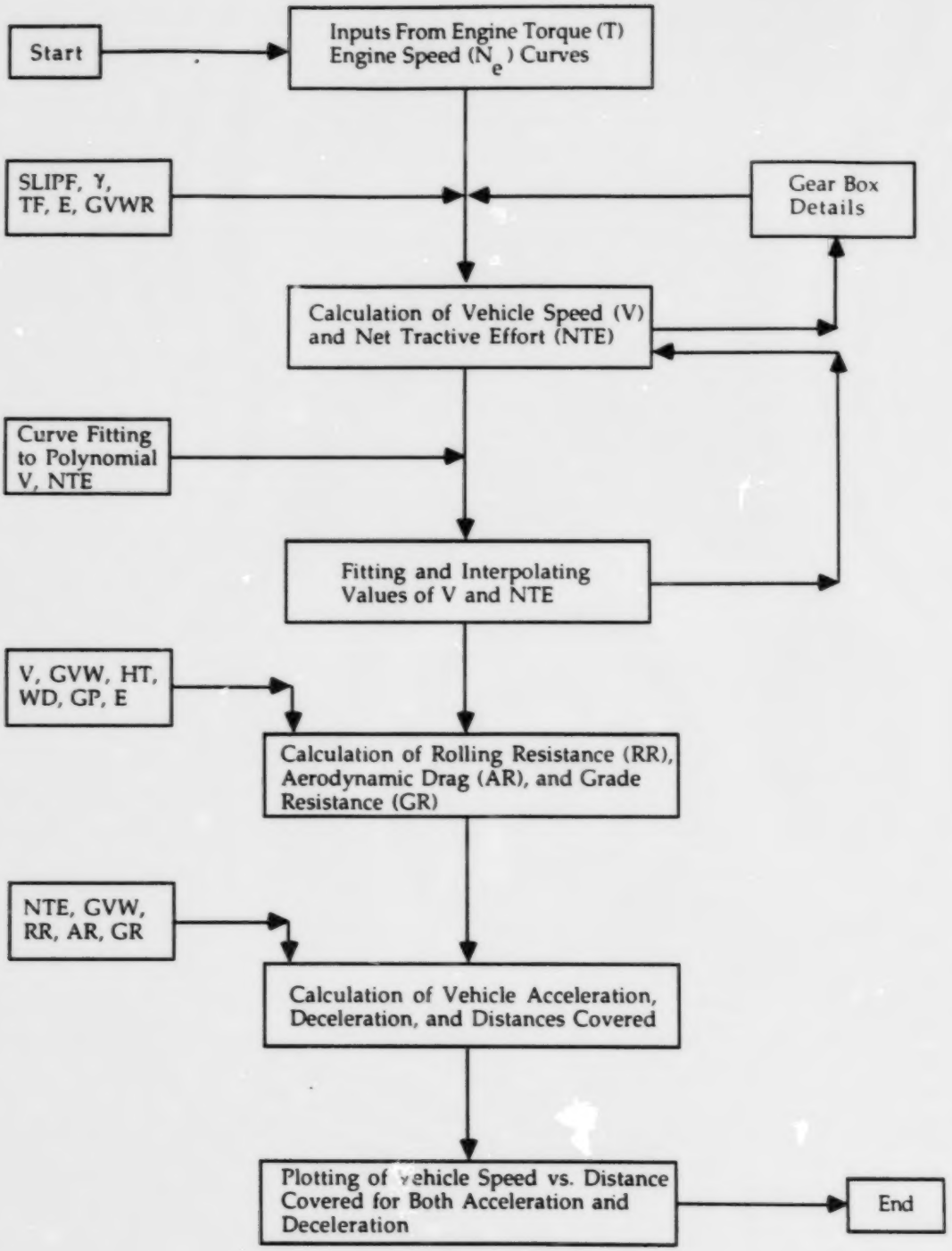
Start
Inputs From Engine Torque (T) Engine Speed (N_e) Curves
SLIPF, Y, TF, E, GVWR
Gear Box Details
Calculation of Vehicle Speed (V) and Net Tractive Effort (NTE)
Curve Fitting to Polynomial V, NTE
Fitting and Interpolating Values of V and NTE
V, GVW, HT, WD, GP, E
Calculation of Rolling Resistance (RR), Aerodynamic Drag (AR), and Grade Resistance (GR)
NTE, GVW, RR, AR, GR
Calculation of Vehicle Acceleration, Deceleration, and Distances Covered
Plotting of Vehicle Speed vs. Distance Covered for Both Acceleration and Deceleration
End

Figure 4.1: Computer Simulation Model based on Truck Ability Prediction Procedure Recommended by SAE.

Table 4.1
Comparison of Modelling Approaches

Factor	Detailed Simulation	SAE Version
Engine power utilization	Yes	No
Tire growth factor	Yes	No
Separate aerodynamic drag components for each truck vehicle unit	Yes	No
Limitation of tractive effort based on road adhesion	Yes	No
Mass moment of inertia of engine and rotating parts	Yes	No
Differentiation between straight truck, semitrailer and double trailer double trailer	Yes	No
Inclusion of gear change delays	Yes (only for research purposes)	No
Applicability to vehicles other than truck	Yes	Yes, with modification
Consideration of static or dynamic load for determining the maximum tractive force due to road-tire adhesion	Yes	No
Driveline resistance	Through efficiency term	Through chassis resistance
Altitude factor for engine power and aerodynamic drag	Can be incorporated	Yes

The inputs for this module are the engine characteristics in terms of engine speed (RPM)-engine torque (N-m) relationship, and the gear ratios in the driveline.

Basic equations as used in the computer program are the modified version of the SAE equations. As used in the computer program, these relationships are all in terms of force having the inputs in S.I. units. As a modification, slippage of the vehicle running gear is also introduced in vehicle speed calculations and instead of using engine horsepower, engine tractive effort (equation 5) is used.

The reader may note that all the variables used in equations (1) to (11), shown below, are expressed in S.I. units and the various conversion factors (Z1 to Z4 and 0.27777) used in these equations provide a link between the equations of the computer program and the equations in the SAE document. For direct correspondence with the computer program, the multiplying factor of 4.448 (in few of these equations), can be replaced by the term $[1/(375 \times Z_1 \times Z_2 \times 0.27777)]$. Also, in equation (11), 9.81 can be can be replaced by $(Z_4 \times 4.448)$.

$$V = ([N_e (SLIPF)]/[C_2 (TF)])(Z_1) \quad (1)$$

$$SLIPF = [1 - (SLIP/100)] \quad (2)$$

$$C_2 = g_g g_a \quad (3)$$

$$NTE = GTE - FR \quad (4)$$

$$GTE = [TC_2 (AF)]/r \quad (5)$$

$$FR = [(1 + 2.0 \times 10^{-7} N_e (GVWR \times Z_4))]/[Z_2 V \times 0.27777] \quad (6)$$

$$AF = (1 - 4.0 \times 10^{-5} E \times Z_3) \quad (7)$$

where

AF — altitude factor for engine performance correction

C_2 — overall gear ratio

E — altitude of operation, above the sea level (m)

g_a	axle gear ratio
g_g	transmission gear ratio
GTE	tractive effort (N)
GVWR	manufacturer maximum gross vehicle mass rating of powered unit (kg)
FR	frictional resistance of chassis (N)
N_e	engine speed (rpm)
NTE	net tractive effort (N)
SLIPF	slippage factor
SLIP	percentage slip of vehicle running gear
r	loaded static radius of tire (m)
TF	tire factor (i.e., tire rpm at the vehicle speed of 1.61 km/h)
T	engine torque (N-m)
V	vehicle speed (km/h)
Z_1	= 1.6093, multiplying conversion factor for mph to km/h
Z_2	= 1.3410×10^{-3}, multiplying conversion factor for N-m/s (watts) to hp
Z_3	= 3.2808, multiplying conversion factor for m to ft
Z_4	= 2.2046, multiplying conversion factor for kg to lb
0.27777	multiplying conversion factor for km/h to m/s

This set of calculations is done for all available gear ratios of the transmission.

4.3 Polynomial Curve Fitting (Module 2)

This module fits the relationship between the Net Tractive Effort and vehicle speed obtained from the previous module to a curve, and then the values of NTE and V are interpolated for every 0.1 km/h interval of vehicle speed.

4.4 External Opposing Forces to Vehicle Motion (Module 3)

This module calculates the rolling resistance , aerodynamic drag and the grade resistance, and finally, the resultant opposing force for each speed interval.

The process is repeated for the entire speed range for all gear ratios. Also, for each grade, the process is repeated.

The calculation of the various resistances is based on the empirical equations and relationships recommended by the SAE with some modifications. Various input and output values are in SI units. These equations are presented below:

1. Rolling Resistance

$$RR = [\{(7.6 + 0.09(V/Z_1)\ GVW \times Z_4)\}/1000] \times 4.448 \quad (8)$$

2. Aerodynamic Drag

$$AR = [0.002\{(HT \times Z_3 - 0.75)WD \times Z_3\}(V/Z_1)^2](AFAR) \times 4.448 \quad (9)$$

$$AFAR = (1 - 6.887 \times 10^{-6}\ E \times Z_3^{4.255})$$

3. Grade Resistance

$$GR = (GP/100) \times GVW \times 9.81 \quad (10)$$

where:

AFAR	altitude correction factor for air drag
AR	aerodynamic drag (N)
GP	percentage of grade
GR	grade resistance (N)
E	altitude of vehicle operation, above the sea level (m)
HT	height of vehicle (m)
GVW	gross vehicle mass (kg)
RR	rolling resistance (N)
WD	width of vehicle (m)
V	vehicle speed (km/h)

Z_1 to Z_4 as defined earlier

This set of calculations is performed for all gears and for all grades ranging from -9% to +9%.

4.5 Vehicle Acceleration (Module 4)

With the known inputs, such as NTE, resultant motion resistance and GVW, the acceleration for each speed interval is calculated for upgrade and downgrade motion. The vehicle (input) speed ranges from zero to the maximum allowed value.

4.6 Vehicle Deceleration (Module 5)

This module is akin to Module 7 in Chapter 3. Also, it is similar to Module 4 of the present model except for the fact that the vehicle enters the grade with the maximum speed and decelerates as it goes up the grade. The power or force available is the regular power or force during negotiation of a typical grade.

4.7 Input Data for the Two Models

The accuracy of prediction of vehicle acceleration and deceleration mainly depends upon the validity of the values of the input parameters and coefficients.

For Model II, the data presented in the latest SAE documents were used in the simulation [9,14]. For Model I, while it takes into account many more factors than Model II, the precise values of some of the input parameters and coefficients required are not readily available. It is believed that if and when more precise data become available, Model I will provide a more comprehensive prediction of truck performance.

Chapter 5

HEAVY VEHICLE PERFORMANCE ON GRADE: DISCUSSION OF MODEL OUTPUT AND COMPARISONS WITH FIELD DATA

5.1 Introduction

In this study, two approaches were developed for the estimation of truck performance on grade, and are covered in Chapters 3 and 4. Selected results of these approaches are shown in Appendices A and B. Also, heavy vehicle grade performance curves are included in the MTO capacity seminar notes, AASHTO's design manual and TRB's Highway Capacity Manual. In addition to model results, field observations of truck speed are available from FHWA, MTO and from studies carried out as a part of this research.

In this chapter, following the interpretation of results obtained from Models I and II, a review of available truck climbing curves is carried out by comparing truck performance estimates obtained from the use of various curves. On the basis of the review of truck climbing speed-distance curves, and the reasons advanced, the use of Model 2 output is recommended for planning and design.

5.2 Interpretation of Model Output

Appendices A and B contain the output of Models I and II. For specified vehicle types and input values, outputs include the deceleration and acceleration characteristics up grade, and the acceleration characteristics downgrade. In the case of Model I, truck type is specified as well and for reasons documented in Chapter 4, Model II provides output for generic types of truck. In both cases, recreational vehicle speed-distance functions are provided as well.

The speed-distance curves represent an estimate of heavy vehicle speed over grades ranging from 0 to 9 percent and from -1 to -9 percent. These functions show that if allowed to travel on grade without interference from other vehicles, a heavy vehicle of specified weight-to-power is likely to follow a speed-distance profile as represented by the computer output included in Appendices A and B.

An examination of results suggests that heavy trucks in a number of instances are not able to reach the desired top speed such as 100 km/h or higher. The reason is that given the weight/power ratio and other transmission characteristics, these

vehicles cannot attain the speed as the power available is low for the given weight limits. In order for such vehicles to attain higher speeds, a change in loading level has to be made.

The use of heavy vehicle speed-distance functions provides an estimate of the speed of the heavy vehicles as well those having to follow slow moving vehicles due to lack of passing opportunities, or in locations where passing is not allowed because of inadequate sight distance. On routes which contain a significant proportion of truck traffic, the critical length of grade is to be estimated by the use of truck speed distance curves. On routes where the majority of slow moving vehicles are RV's, the critical length of grade is to be established by using the curves for recreational vehicles.

In mixed traffic of high volume, both trucks and recreational vehicles present in the stream impede traffic and therefore should be taken into account in climbing lane studies. It is known that trucks tend to impede recreational vehicles more than the passenger cars. Such a study, however, has to go beyond the use of climbing curves.

5.3 Basis for Comparison

The AASHTO, TRB and Carleton University curves are derived from computer models. Given that there are differences in model form and input values, the outputs cannot be compared in a very strict fashion. Also, truck characteristics differ substantially in their individual combinations of engine, transmission, axles, aerodynamics and other characteristics. However, all curves that have been reported estimate on-road truck performance. Similar considerations apply while examining the curves for recreational vehicle performance. Consequently, it is desirable to review various curves in order to learn of their similarities and differences.

The main factor that can be used as a basis of comparison of model outputs is the weight-to-power ratio. Other factors, such as vehicle design characteristics are not reported by other researchers. These are not considered explicitly in this review.

The output of any model requires verification by comparing such estimates with field observations. In the review of curves, a comparative assessment of performance recorded in the field with model outputs is required. There are, however, difficulties involved in finding relevant factors with a high degree of confidence. Field observations of vehicle speed cannot be directly matched with the weight to power ratio of vehicles. From statistical analyses, performance levels could be matched with the percentile of vehicle population (e.g., 12.5th percentile vehicle performance, 50th percentile vehicle performance).

5.4 Comparison of Model Output

In order to appreciate the similarities and differences between the outputs of models developed in this study as well as those reported in the literature, a number of comparisons are made. In general, outputs of Models I and II (given in Appendices A and B) show similar performance for various vehicles simulated in this study. A comparison of Model I and II outputs suggests that the detailed simulation model (i.e., Model I) is more sensitive to the extreme loading levels and speeds than Model II. The relative insensitivity of Model II might be explained by its aggregate nature.

Selected outputs of Models I and II are compared in terms of crawl speed achieved by vehicles for grades of 3% and 5%. (Table 5.1). The heavy truck of 180 kg/kw and the recreational truck of 40 kg/kw are used for comparison. The entry speed of 90 km/h is used. Also noted in this table are crawl speeds estimated by speed-distance curves available from other sources.

In the comparison of results obtained from Models I and II, it should be recognized that due to different vehicle engine and transmission specifications used for simulation runs, there can only be a general similarity of results. Inputs used for the Carleton University models are noted in Appendices A and B.

Model I outputs reflect the characteristics of vehicles simulated -- namely engine, transmission and other characteristics. Due to the stronger influence of these characteristics than the generic nature of the vehicle (i.e., straight truck, semitrailer, double trailer), model outputs in general do not show an appreciable difference among the various types of trucks. However, in the case of 180 kg/kw, the performance of the double trailer falls slightly below other truck types.

In a second set of comparisons, outputs of two models developed in this study are compared with those of AASHTO and TRB. Also, included in this comparison is the set of curves that is contained in the MTO capacity seminar notes and the RTAC's Manual for Geometric Design. An examination of the estimated performance suggests that the Carleton University models estimate performance that is similar to those of TRB and AASHTO. Model II results correspond reasonably well with those of the AASHTO and TRB.

The truck speed-distance curves contained in the MTO Capacity Seminar Notes and RTAC's Geometric Design Manual are specified to represent a vehicle with weight/power ratio of 200 kg/kw (329 lbs/hp) but bear a close resemblance to the AASHTO and TRB curves for the 300 lbs/hp (about 180 kg/kw) power-to-weight

ratio. A truck with a 200 kg/kw level of loading is not likely to achieve the speeds shown in Table 5.1. For planning and design, a truck with 200 kw/kg weight-to-power ratio should not be used for most routes in Ontario.

Table 5.1
Comparison of Vehicle Performance Estimated by Various Models: Selected Vehicles, Crawl Speed, Km/h

	Grade	
	3%	5%
Carleton University Model I		
180 kg/kw Straight Truck	44	28
180 kg/kw Semitrailer	42	28
180 kg/kw Double Trailer	42	27
40 kg/kw Recreational Vehicle	90	74
Carleton University Model II		
180 kg/kw Truck	42	30
40 kg/kw Recreational Vehicle	89	77
MTO Capacity Seminar Notes and RTAC Geometric Design Manual		
200 kg/kw Truck	42	30
AASHTO		
300 lbs/hp (180 kg/kw) Truck	43	29
TRB		
300 lb/hp (180 kg/kw) Truck	43	29

Sources: Appendix A and B for Carleton University Models. See References 2,3,4, and 5 for other estimates noted in Table 5.1.

5.5 Comparison of Model Output and Field Data

Three sources of field data are used here to check estimated truck performance. These include field studies carried out as a part of the present study, the MTO speed data obtained at various times in the past, and truck speed data obtained by a study sponsored by the FHWA.

Carleton University's field data were collected at three sites on Highway 17 and one site on Highway 417. In all cases, speed readings were taken at the approach to the grade and upgrade. Table 5.2 shows site characteristics. Grades ranged from 3% to 5.3%. Length of grade varies from 200m to 1300m. It should be noted that due to budget constraints, weight/power information was not collected as a part of field studies.

Table 5.2

Sites for Speed Studies

Site:	Site 1	Site 2	Site 3	Site 4
Location	HW #17 Near Exit for Pembrook	HW #17 Near Exit for O'Brian Renfrew	HW#17 Near Exit for Granger Park Rd.	HW#417 Near Moodie Dr.
Grade	5.3%	3.5%	3.0%	3.0%
Length	200m	1000m	1300m	900m

During the off-peak time periods chosen for field studies, traffic volumes at all sites were not high enough to cause queues upgrade. The speed of trucks and other vehicles, therefore, reflect almost free flow conditions. Any drop in speed upgrade is caused by the inability of vehicles to maintain their approach speed. The choice of sites and the off peak times for field studies are believed to be appropriate for this study.

Field data are summarized in Tables 5.3 and 5.4. In all cases, mean speed, median speed and standard deviation are shown for approach as well upgrade locations for each site. The drop in speed for trucks is in line with their capability to travel upgrade. On the other hand, the drop in speed for passenger cars and recreational vehicles is higher than expected. Obviously, the

drivers of private automobiles and recreational vehicles are not utilizing full engine power in a manner similar to professional truck drivers. Another reason for a general lack of correspondence of model results and field data for the recreational vehicle for low grades could be attributed to the effects of geometrics on driver behaviour.

Table 5.3

Field Data: Truck and RV Speed -- Km/h

	Site 1	Site 2	Site 3	Site 4
Truck				
Mean Speed				
Approach	71.1*	96.7	92.5	93.5
Upgrade	65.6	74.0	74.2	67.8
Median Speed				
Approach	68.0*	98.0	93.0	94.0
Upgrade	68.0	77.3	74.1	69.0
St. Deviation				
Approach	16.6	7.5	11.0	10.6
Upgrade	12.0	11.3	7.2	9.1
Recreational Vehicle				
Mean Speed				
Approach	80.0*	98.8	94.1	89.4
Upgrade	67.3	72.9	76.0	67.8
Median Speed				
Approach	79.0	96.5	92.0	88.0
Upgrade	74.0	78.8	77.3	68.0
St. Deviation				
Approach	3.6	5.5	9.1	7.8
Upgrade	8.1	14.8	7.2	8.0

* The approach speed for vehicles for Site 1 were low due to the presence of a railway grade crossing near the speed measuring station. In particular, trucks reduced their speed at the grade crossing, thus affecting entry speed.

Mean approach speed of trucks at Site 2 is higher than for Sites 3 and 4 for the reason that just prior to entering the upgrade section under observation, a negative grade enabled

vehicles to gain speeds than would be the case for level tangent sections of the highway. The mean speeds of trucks and recreational vehicles for Site 3 are not too far above the posted maximum speed of 90 km/h. On the other hand, despite the posted speed of 100 km/h at Site 4, the average speed of truck and recreational vehicles is much lower than the posted maximum speed. The mean speed of automobiles is the same as the posted top speed allowed.

Table 5.4

Speed Data (Km/h): Automobile

	Site 1	Site 2	Site 3	Site 4
Automobile				
Mean Speed				
Approach	90.6	101.5	102.5	99.8
Upgrade	82.2	82.4	85.5	75.0
Median Speed				
Approach	92.0	101.0	101.0	102.0
Upgrade	81.5	83.7	85.3	74.0
St. Deviation				
Approach	14.8	8.7	11.6	9.7
Upgrade	9.4	8.1	7.3	7.8

Further comparisons can be made to assess the validity of the output of the Carleton University models with field data reported above, other field data obtained by a study team sponsored by the Federal Highway Administration (FHWA) (U.S.A.), and results obtained from the use of speed-distance curves published by AASHTO and TRB [4,5,7].

Table 5.5 presents selected assessments of estimated performance of heavy vehicles for study sites 1 to 4 against field data. Model II output is used for upgrade speed, and field data used for checking the validity of model output correspond to 50 percentile and 12.5 percentile speed. In the case of the recreational vehicle, only the 50 percentile speed is used. Model II output is used to estimate performance of a variety of weight/power ratios. The 50 percentile speed is used to represent average vehicle performance.

Table 5.5

Field Data and Comparison With Model Output

	Site 1	Site 2	Site 3	Site 4
Site Data				
Grade (%)	5.3	3.5	3.0	3.0
Length (m)	200	1000	1300	900
Field Data: Truck				
50 percentile speed (km/h)	68	77	74	69
12.5 percentile speed (km/hr)	48	65	64	56
Estimated Performance (Model II Results)*				
Speed in km/h for				
60 kg/kw truck	73	83	83	84
120 kg/kw truck	63	67	62	67
180 kg/kw truck	52	52	50	57
Field Data: Recreational Vehicle				
50 percentile speed (km/h)	70	79	77	68
Estimated Performance (Model II Results)				
40 lbs/hp RV	78	87	89	89

* Please see Table 5.3 for approach speed.

An examination of field data and speeds estimated from Model II output suggests that the 50th percentile truck speed corresponds to approximately a weight/power ratio of 120 kg/kw. For all practical purposes, the average truck performance can be estimated from the use of 120 kg/kw curves. The 12.5th percentile speed, for two out of four sites, can be approximated with the 180 kg/kw ratio.

The speeds of recreational vehicles estimated by the model are consistently higher than the 50th percentile speed measured in the field. The reason for such a discrepancy, as noted earlier, relates to driver use of less than maximum power on grade.

Further comparisons can be made to assess the output of the Carleton University model with field data obtained by a study team sponsored by the U.S. FHWA, and model results obtained from the use of AASHTO and TRB curves (Table 5.6). The U.S. field data show that the 50th percentile speed of double trailers is less than that of straight trucks and semitrailers. Carleton University Model II output for a generic truck falls between double trailers and straight truck and semitrailer. Model I output for double trailer compares well with field data but field and model data differ in the case of other vehicle types. Results of Model II and other speed-distance curves also appear to underestimate performance of straight truck and semitrailer. A reason for the difference could be that the weight/power ratios of 120 kg/kw (200 lb/hp) and 180 kg/kw (300 lb/hp) do not necessarily correspond with the 50 and 12.5 percentile straight truck and semitrailer respectively.

A final comparison is made by checking model output against MTO and Carleton University field data. For a 5% upgrade, Model II output for light and heavy trucks is plotted in Figure 5.1. Also plotted are MTO field data that represent average and loaded trucks. The field data plots fit very well within the envelope created by the theoretical results obtained from the model.

Another set of field data obtained from the MTO sources for a 5% upgrade is shown in Figure 5.2 against the output of Model II. It appears that the speed profile obtained from MTO's tractor trailer tests is very close to the 180 kg/kw output of Model II.

Finally, a comparison of Model II output and field data collected at Site 3 is shown graphically in Figure 5.3. The theoretical estimates obtained from Model II for a 3.5% grade are plotted for the 60 and 180 kg/kw power/weight level. The actual speed drop from the approach is shown and from this a speed drop curve for assumed 90 km/h entry speed is drawn. The estimated speed drop profile fits very well within the theoretical speed-distance curves estimated by Model II.

Table 5.6

Comparison of Model Results and U.S. Field Data

	Crawl Speed (km/h)	
	3% Grade	5% Grade
U.S. Field Data:		
50 percentile vehicle		
Double trailer	50	36
Straight truck and Semi-trailer	61	45
12.5 percentile truck		
Double Trailer	42	29
Straight truck and Semitrailer	50	34
AASHTO Curves, 300 lbs/hp	43	30
TRB Curves		
200 lbs/hp	59	42
300 lbs/hp	43	29
Carleton University		
Model I Output		
120 kg/kw Double Trailer	61	42
180 kg/kw Double Trailer	42	27
120 kg/kw Semitrailer	59	41
180 kg/kw Semitrailer	42	28
Model II output		
120 kg/kw	54	41
180 kg/kw	42	30

Source: U.S. Field data are contained in Reference 7. AASHTO speed-distance curves are reported in Reference 4. Carleton University Model outputs are included in Appendices A and B of this report.

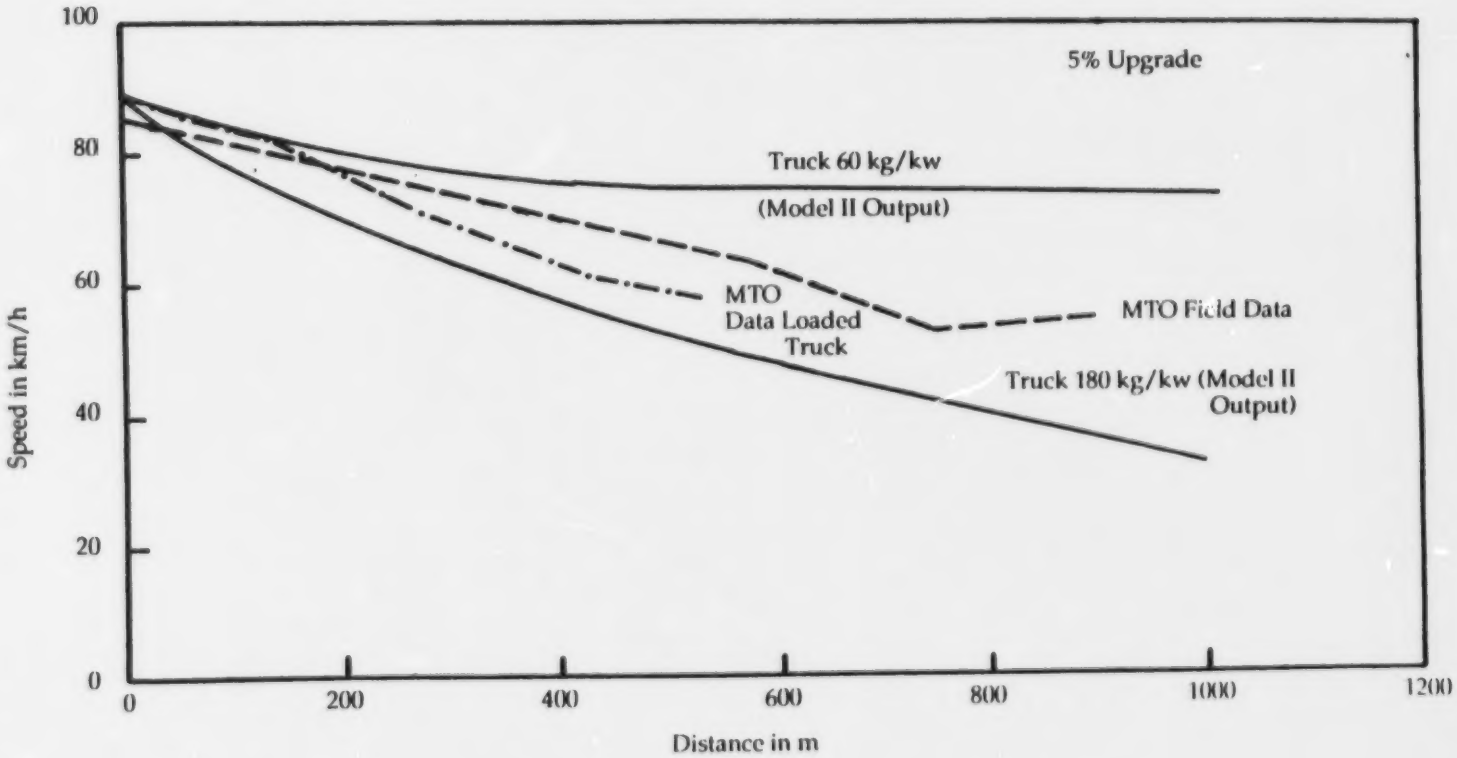

Figure 5.1: Comparison of Model II Output and Ministry of Transportation, Ontario Field Data, 5% Upgrade.

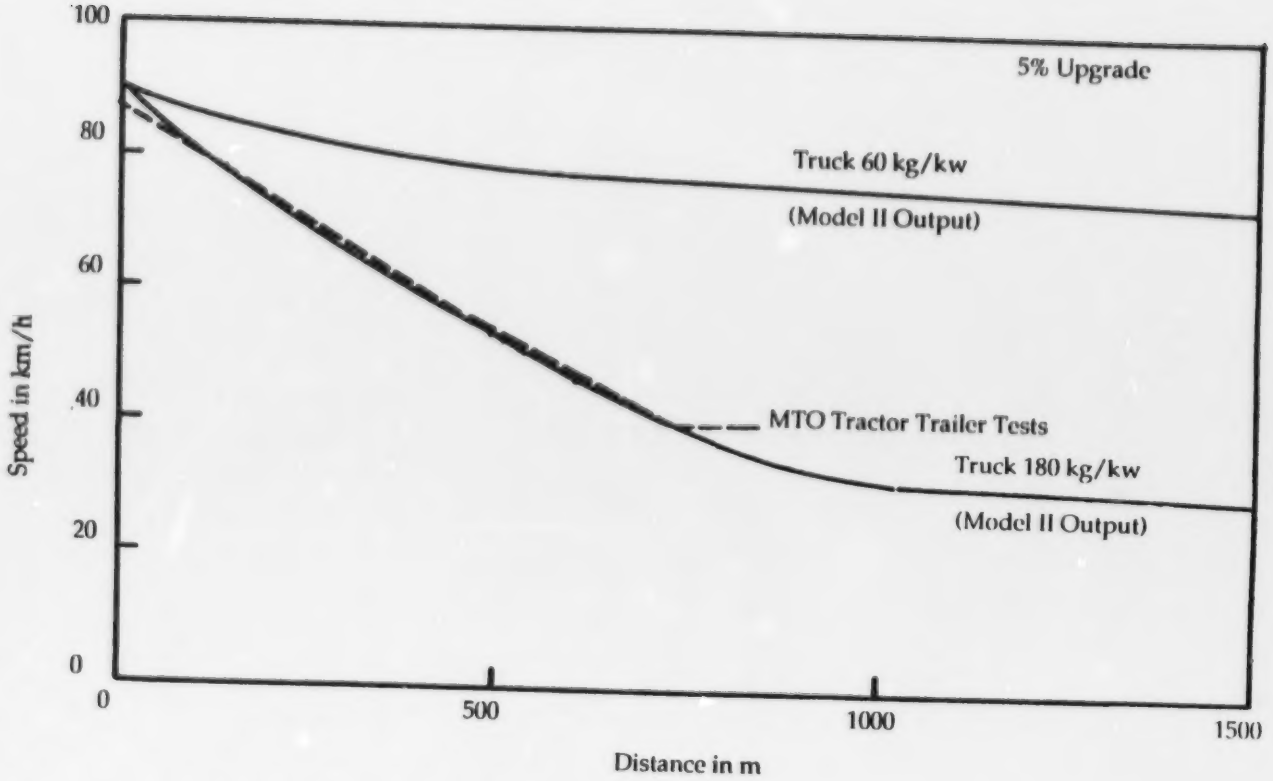

Figure 5.2: Comparison of Model II Output and Ministry of Transportation, Ontario Tractor Trailer Test Data, 5% Upgrade

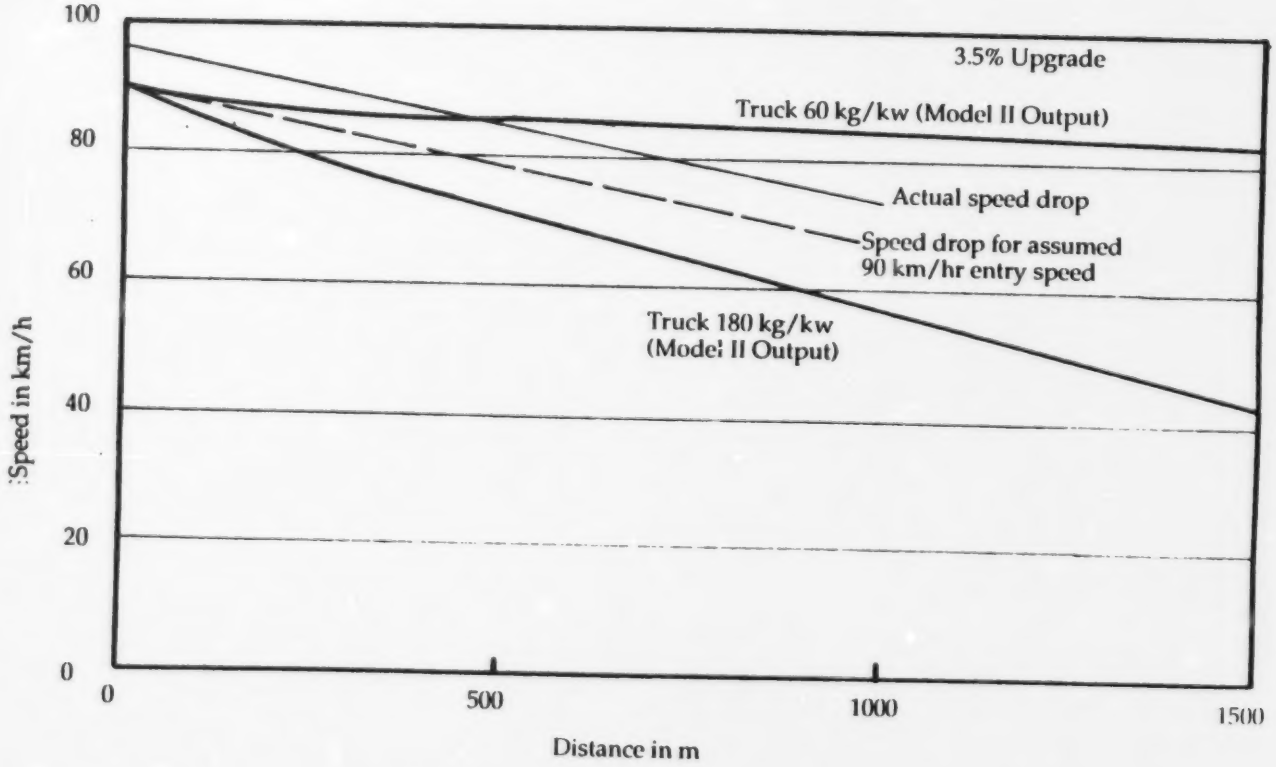

Figure 5.3: Comparison of Model II Output and Field Data (Site 3), 3.5% Upgrade

Chapter 6

REVIEW OF CLIMBING LANE WARRANTS

6.1 Climbing Lane Decision

It has been a long standing practice in highway design to consider the use of three lane cross sections at appropriate locations on two lane highways with one lane intended for the use of slow moving heavy vehicles. Such cross sections are generally used as spot improvements to steep sustained grades. Heavy trucks and other heavy vehicles cannot maintain speeds desired by the operators of passenger cars.

The slow speeds of heavy vehicles, particularly in situations that offer no or low opportunities for passing slow moving vehicles, cause platoons, increase delay to road users and reduce the capacity of two lane highways. Drivers under such conditions are known to make unsafe passing manoeuvres. Statistics suggest that safety hazards rise with increasing speed differential between speed of slow moving vehicles and those vehicles that can maintain desirable speeds (Figure 6.1). As can be seen in Figure 6.1, the accident involvement rate rises rapidly when the reduction in speed of slow moving vehicles exceeds 15 km/h along the grade.

The variables that enter into the decision to provide climbing lanes include:

- safety of road users,
- operational efficiency -- minimization of delays caused by slow vehicles on grade,
- cost of providing climbing lanes.

Past research indicates that safety has been an important consideration in the decision to provide climbing lanes and in their design [17,18,19,20]. The safety objective has led to the use of the speed differential explicitly in the warrants or recommended practices. Climbing lanes provide safe passing opportunities.

The objective of improving operational efficiency of highways at locations of steep sustained grades implies the reduction of percent time delay, improving average travel speed and reducing platoons.

The cost variable, as noted in the cost-effectiveness section (Section 6.4) is not addressed explicitly at this time. It is nevertheless an important consideration since efficient use of

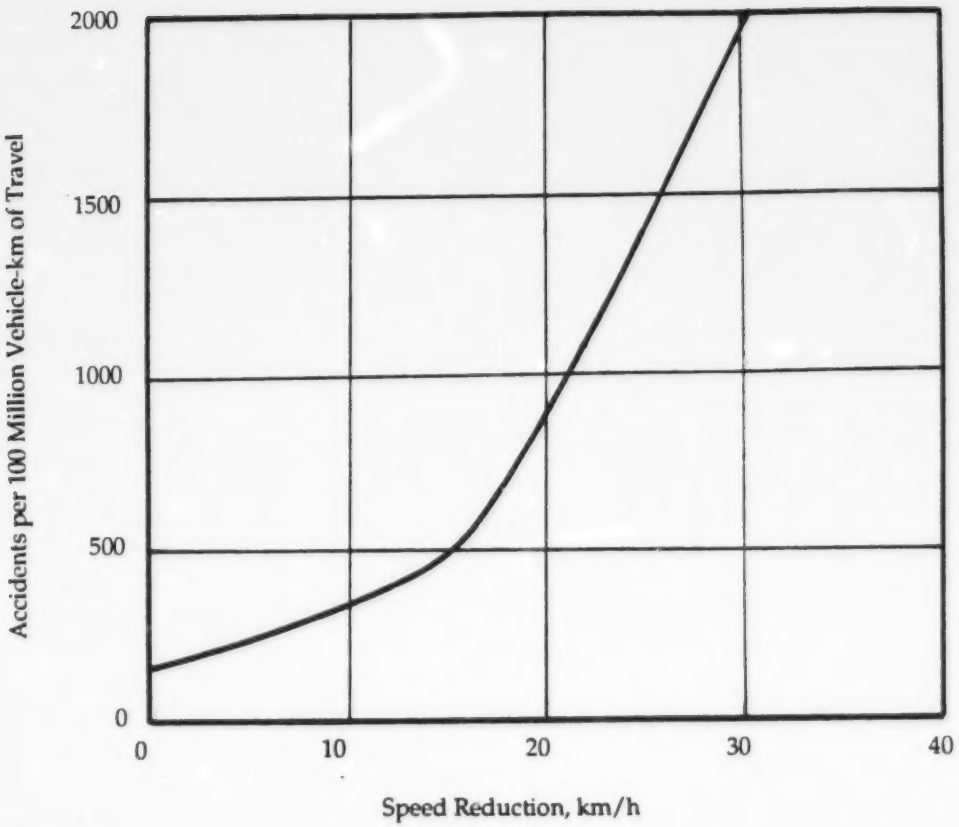

Figure 6.1: Accident Involvement Rate of Trucks on Two Lane Roads

infrastructure investment capital is to be demonstrated.

For the examination of candidate locations for the provision of climbing lanes and the study of warrants, speed reduction curves for trucks are required. Lengths of grade that cause speed reduction of various magnitudes below the posted maximum speed (or desired speed) are shown in Figures 6.2 and 6.3. These have been derived from vehicle speed-distance curves presented in Appendix B for initial speed equal to 90 km/h. Similar curves could be developed for other initial speeds.

6.2 Current Warrants for Climbing Lanes

Highway transportation agencies and others with a mandate to advance the state of knowledge in highway planning and design have produced criteria for the provision of climbing lanes. Such criteria, also referred to as warrants, assist the planning and decision making process without resorting to totally ad hoc approaches. Table 6.1 presents a comparison of warrants of a number of notable agencies and associations.

Relevant factors that are used as guidelines for the provision of climbing lanes relate to overall traffic volume, truck traffic, level of service, and speed reduction. To evaluate speed reduction, truck type or weight/power ratio are suggested for use by the designers. The volume warrants, although difficult to specify, are intended to serve as a proxy for cost-effectiveness considerations.

There is much diversity in the warrants for climbing lanes as defined by various agencies. Also, in the case of the Transportation Research Board warrants, there is little explanation of the magnitude of some specific items (i.e, traffic volume, truck traffic upgrade, etc.).

6.2.1 Ministry of Transportation, Ontario Warrants

Geometric Design Standards for Ontario Highways (1985) and other documents make reference to the provision of climbing lane for safety and operational efficiency. The critical length of grade is to be defined for a design truck of 200 kg/kw and a speed reduction of 15 km/h. The consideration of the level of service on grade is implicit in the guidelines requiring that the level of service should not drop by more than one interval below the design level of service for the highway. The level of service criterion that is recommended suggests that a drop in one or more level of service (e.g., from B on level approach to C or lower on grade) provides a basis for considering a climbing lane.

The warrants for the design involve locating the climbing lane at that point where the speed of a design vehicle drops

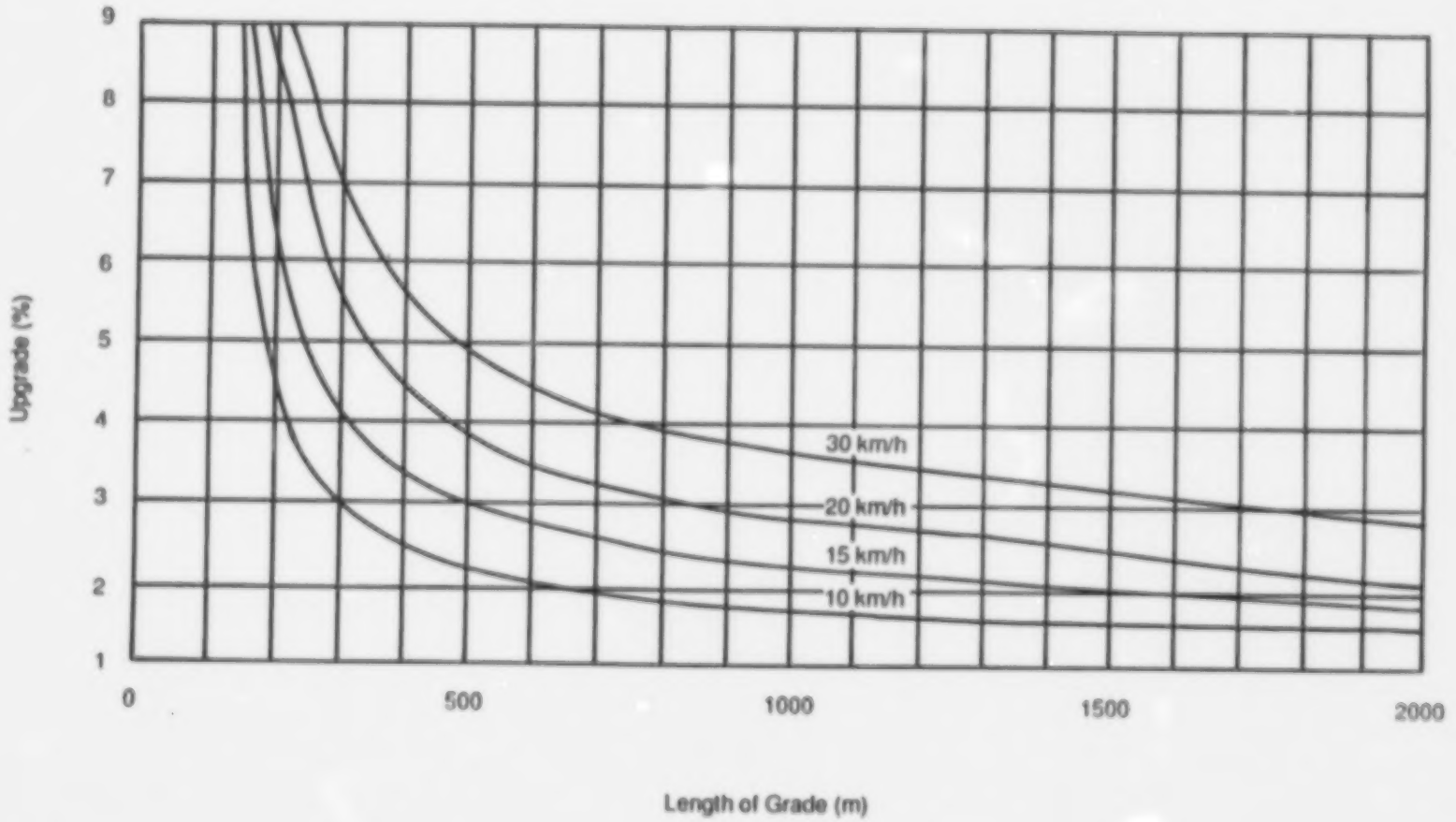

Figure 6.2: Critical Length of Grade, 120 kg/kw Truck

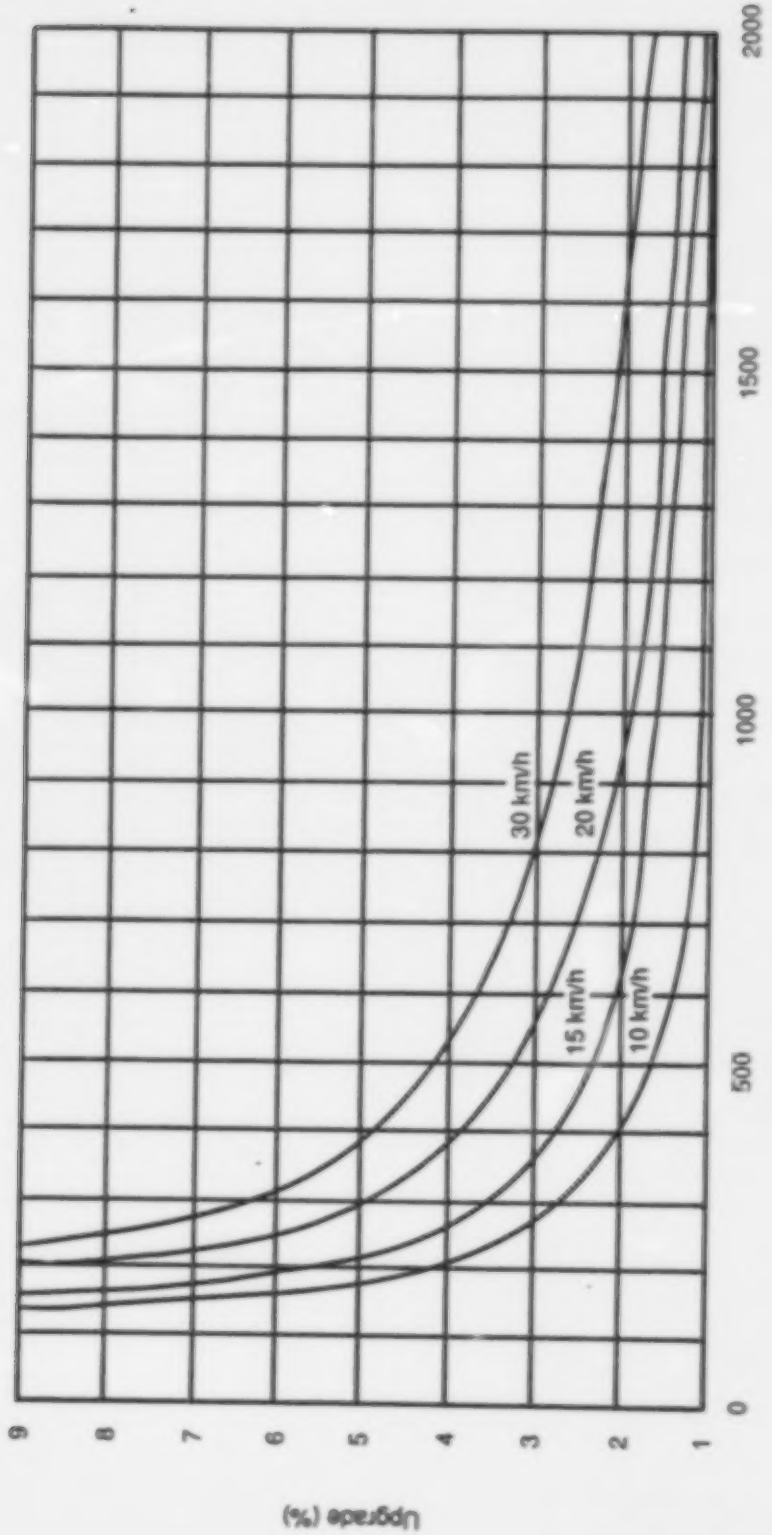

Figure 6.3: Critical Length of Grade, 180 kg/kw Truck

below the operating speed by more than 15 km/hr and preferably to end it where trucks are able to regain speed so that is not lower than 15 km/h below the operating speed of the road. For two lane roads, the operating speed of 90 km/h is used although in a number of rural areas, average operating speeds are as high as 100 km/h.

The cost of climbing lane is another consideration in the process of providing climbing lanes. However, at present, there is no formal basis for comparing the cost-effectiveness of climbing lanes.

Table 6.1

Comparison of Warrants and Recommended Practice

Factors	MTO	RTAC	AASHTO	TRB
Upgrade Traffic Flow Rate (vph)	No	No	No	Yes
Upgrade Truck Flow Rate	No	No	No	Yes
Level of Service on the Grade	Implicit	No	No	Yes LOS E or F
Reduction in Level of Service (from the approach segment to the grade)	Yes; one or more	No	Yes; one or more	Yes; two or more
Speed Reduction for a Typical Heavy Truck:				
. Speed Reduction (km/h)	15	15	16	16
(mph)			10	10
. Truck Wt/Power (lbs/hp)			300	200 & 300
(kg/kw)	200	200		

6.2.2 RTAC Guidelines

According to the RTAC Manual for Geometric Design of Highways, "warrants for the provision of climbing lanes are:

. volume warrant criteria,
. speed reduction and critical length of grade criteria.

The basis for the provision of a climbing lane is related to highway capacity and passing opportunity. The use of the level of service criterion is specified in terms of a drop in this indicator of service quality on the up grade. The provision of a climbing lane is stated to reduce the percentage of grade-affected vehicles in the through lane, and therefore to accommodate the remaining demand volume [3].

Safety is also mentioned as a consideration. It is recognized by RTAC guidelines that the more a vehicle deviates from the 85th percentile speed, the greater the probability of accident involvement. From a safety standpoint, the 15 km/h speed reduction value is suggested as the criterion for speed drop.

6.2.3 AASHTO Warrants

Prior to the publication of the current design guidelines in 1984, AASHTO used a speed reduction of 15 mph (24 km/h) and of 40 mph (64 km/h) in entry speed. The 1984 manual recommends a speed reduction of 10 mph (16 km/h) and an entry speed of 55 mph (90 km/hr). That is, AASHTO warrants a climbing lane at locations where the speed of a 300 lb/hp (180 kg/kw) truck is reduced by 10 mph (16 km/h) or more.

As for traffic and cost criteria, it is stated that the volume and percentage of heavy trucks should justify the added cost. However, no procedure for incorporating these variables is given. In the establishment of new warrants, the accident involvement rate has been a major consideration [4]. A drop in the level of service is also used as an element of warrants -- one level poorer than desired -- from B to C, or from C to D. [4].

It is suggested that climbing lanes for multilane highways incorporate the consideration of critical length of grade, although warrants are not defined.

AASHTO design manual contains speed-distance curves and length of critical grade. However, it has been stated in the literature that for a number of routes that serve only a very small percentage of heavily loaded trucks, the AASHTO curves underestimate truck speed. Consequently, it has been stated that the 10 mph (16 km/h) guide is somewhat conservative in determining critical length of grade [7].

6.2.4 Transportation Research Board Guidelines

The 1985 Highway Capacity Manual provides general guides for

the provision of climbing lanes on two lane highways. In the case of multilane highways, there are no well defined guides for the consideration of climbing lanes [5].

According to TRB, one set of criteria that would reflect the economic basis of climbing lane decisions for a two lane highway is:

1. Upgrade traffic flow rate exceeds 200 vph,
2. Upgrade truck flow rate exceeds 20 vph,
3. One of the following conditions exists:
   - Level of service E or F exists on grade,
   - A reduction of two or more levels of service is experienced when moving from the approach segment to the grade,
   - A 10-mph or greater speed reduction is expected for a typical heavy truck.

6.3 Design Guidelines

Two aspects of design are of interest here: the starting location and the length of lane. Literature study as well as preliminary tests conducted by a microscopic simulation model, namely the TWOPAS model developed for the FHWA (U.S. DOT) suggest that [4,20,21]:

- the climbing lane should start at the point where the drop in speed of a specified heavy vehicle exceeds 15 km/h, and
- the climbing lane should preferably end at the point beyond the crest where truck speed comes within 15 km/hr of the speed of other vehicles.*

In case of special conditions such as right-of-way or other restrictions, upgrade approaches or other conditions, the climbing lane could start prior to the location suggested above. Also, in the case of very long climbing lanes required on the basis of the application of the above noted guidelines, tradeoffs in terms of cost-effectiveness could be investigated.

Another study states that the most cost-effective location for the construction of a climbing lane is near the midpoint of the upgrade [22]. This study also suggests that the most cost-effective length for the construction of a climbing lane is 460 m (excluding the entrance and exit tapers). The latter views have not been substantiated by other researchers. However, the RTAC Geometric Design Manual recommends that in order to allow for completion of an overtaking manoeuver, a minimum length of climbing lane of 500m be provided [3]. The Ministry of Transpor-

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* Additional factors could influence the design of climbing lanes. Sight distance is an important consideration. Furthermore, the site under consideration may qualify for a passing lane.

tation, Ontario uses 1.5 km as the minimum length of a climbing lane.

6.4 Example Applications of Warrants

Assume that the following profile of a highway is under consideration for truck climbing lane. The design hourly volume is to be varied from 300 to 1500 vehicles per hour, with 15% of the traffic classified as trucks, 5% as recreational vehicles and a negligible amount of buses. Sixty percent of traffic is in the upgrade direction. While the exact composition of truck traffic is unknown, it believed that heavy trucks (represented by kg/kw of 180) are a part of the traffic stream. The operating speed can be assumed to be 90 km/hr on level tangent. Sections 1 and 2 contain grades that are known to cause truck speed reductions. Section 1 is a typical case of rolling terrain while section 2 can be viewed as a hilly area. The DHV is 17.4% of the AADT. It is of interest to investigate whether truck climbing lanes are warranted and to provide sufficient information for designing such facilities.

In the following section, an illustration of the cost-effectiveness of warrants is to be provided on the basis of the parameters of these examples.

Section 1

Distance (m)	0m	700m	1000m	1700m
Grade (%)		+2%	+4%	-1%
Length (m)		700m	300m	700m

Section 2

Distance (m)	1700m	2700m	3700m	4900m
Grade (m)		0%	7%	0%
Length (m)		1000m	1000m	1200m

In the case of section 1, since no single grade exceeds 4% or total length of composite (positive) grade does not exceed

1220m, the use of average grade is permitted by the Highway Capacity Manual of the TRB [5].

Total rise = 700x0.02 + 300x0.04 = 26m
Average (up) grade = (26/1000) x 100 = 2.6%

Now, speed of heavy truck of kg/kw of 180 can be estimated at various locations along the positive grade by using the curves marked "deceleration upgrade" (Appendix B). As an alternative to using the average grade of 2.6%, the detailed approach of estimating truck speed on the +2% and then the +4% grade can be used. The results are identical.

Findings are noted in the figure shown below. The speed at the crest is 62 km/h. Next, this speed is used as the starting point in the appropriate set of curves marked "acceleration downgrade" and the speed of truck is estimated for the downgrade section. The results are noted in the diagram shown below.

The diagram also notes the location where the speed of truck drops 15 km/h below the highway speed (i.e., 75 km/h) and that location where the truck regains speed to the 75 km/h level. These locations are the beginning and the ending point of the truck climbing lane. The length of the truck climbing lane for the heavy truck amounts to 725m. The length of climbing lane is approximated by tangents rather than length of vertical curves. Transition distance is in part included in the estimate of climbing lane.

Section 1

				crest		
Distance (m)	0	650	700	1000	1375	1700
Heavy (180 kg/kw) truck speed (km/h)	90	75	74	62	75	83
Truck climbing lane location and length (m) based on 180 kg/kw truck		725m				

In the diagram shown below, truck speed along the road for the typical (average) truck, characterized by a weight/power ratio of 120 kg/kw, is shown as well for illustration purposes. The locations where truck speed drops to 75 km/h, and where it is regained following acceleration are noted. The rather short length of climbing lane has to be extended to 500m level for improved operations.

In the case of Section 2, speed of a heavy truck (180 kg/kw is estimated from the speed-distance curves marked "deceleration upgrade" (Output of Model II, Appendix B). Truck climbing lane is located from the distance marked as 2900m from the initial position to 4900m. Truck speed is estimated to be below 75 km/h for the 20000m long climbing lane. The speed at the crest is 22 km/h.

Section 1

Distance (m)	0	700	775	1000	1125	1700
Typical (120 kg/kw) truck speed (km/h)	90	78	75	68	75	90
Truck climbing lane (m)			350m -- use 500m			

Note: This design is not used in the following analyses.

Section 2

Distance (m)	1700	2700	2900	3700	4900
Grade	0%	7%		0%	
Truck speed (km)	83	90	75	22	75
Truck climbing lane			2000m		

Since a number of warrants are reviewed, including those of the Ministry of Transportation, Ontario, and since they require the estimation of the level of service experienced by traffic on grade, the next step is to estimate level of service for cases of "without climbing lane" and "with climbing lane". Guidelines provided by the Highway Capacity Manual of the Transportation Research Board can be used to analyze the upgrade section "without climbing lane". Since no methodology is given in the HCM for analyzing the case of upgrade section "with climbing lane", an assumption about the extent of level of service improvement has to be made at this stage of research in climbing lane cost-effectiveness.

The procedure followed here can be shown as a number of steps:

1. Definition of characteristics the roadway:
   . grade (or average grade for composite sections),
   . geometrics; presence/absence of climbing lane
   -- treated as an auxiliary lane,
2. For the relevant range of expected level of service or speed on grade for the entire stream of traffic, selecting the v/c ratios from the HCM,
3. Estimating the values of the following adjustment factors:
   . f_d = adjustment for directional distribution,
   . f_w = adjustment for narrow lanes and restricted shoulder width,
   . f_g = adjustment factor for the operational effects of grades on passenger cars,
   . f_{hv} = adjustment factor for the presence of heavy vehicles in the upgrade traffic stream.
4. Estimation of service flow rate for the level of service or or speed:

$$SF = 2{,}800 \times (v/c) \times f_d \times f_w \times f_g \times f_{hv}$$

5. Comparison of the desired DHV with the estimated SF in order to assess the likely level of service and speed for the upgrade direction.

6. For the "with climbing lane" case, a v/c ratio can be assumed that corresponds to the approach level of service or one level of service higher than for the case of "without climbing lane". Steps 2 to 5 are to be repeated for the estimation of the resulting upgrade speed and the final level of service following the use of necessary adjustment factors.

The calculations are repeated for the cases of overtaking allowed (i.e., 0% no passing zones) and no overtaking allowed (i.e., 100% no passing zones). Estimates of upgrade level of service and operating speed for "without climbing lane" case are shown in Table 6.2.

Up to now, sufficient information has been generated that is required for the application of warrants to the cases studied. For the sake of illustration, the DHV level of 300 vph is used to indicate whether warrants of selected agencies are met or not. Table 6.3 suggests both Sections meet the truck speed drop criterion of the MTO and the TRB. Section 1 with 2.6% grade does not meet the level of service criterion of the MTO while the hilly Section 2 satisfies this warrant.

At the DHV of 300 vehicles/h, both sections do not meet the upgrade flow traffic criterion of the TRB, although the upgrade truck flow rate is met. The remaining criteria are met by both sections (Table 6.3).

Table 6.2

Upgrade Level of Service and Operating Speed Without Truck Climbing Lane

DHV	0% No Passing Zones		100% No Passing Zones	
	Level of Service	Operating Speed (km/h) (km/h)	Level of Service	Operating Speed (km/h) (km/h)
Section 1, 2.6% Average Grade (Rolling)				
300	A	90.0	A-B	84.5
500	A-B	84.5	B	80.5
1000	B	80.5	C	72.5
1500	C	76.5	C	72.5
Section 2, 7% Grade (Hilly)				
300	C	76.5	C	72.5
500	C	72.5	D	64.4
1000	C	72.5	E	48.3
1500	D	64.4	E	48.3

The conclusion is that according to the MTO warrants, at the DHV of 300, Section 1 does not qualify for a climbing lane and Section 2 does pass MTO warrants. Both sections do not meet the TRB warrants of volume of traffic up grade.

Table 6.3

Application of Warrants: Sections 1 and 2, DHV=300

Agency and Factor	Section 1		Section 2	
	Overtaking Permitted	Without Overtaking	Overtaking Permitted	Without Overtaking
MTO				
Heavy truck speed reduction	Yes	Yes	Yes	Yes
Drop in level of service upgrade	No	No	Yes	Yes
TRB				
Upgrade flow of 200 vph	No	No	No	No
Upgrade truck flow rate of 20 vph	Yes	Yes	Yes	Yes
One of The Following:				
. LOS E or F	No	No	No	No
. Reduction of Two or More LOS	No	No	No	Yes
. Truck Speed Reduction of 15 km/h	Yes	Yes	Yes	Yes

6.5 Cost-Effectiveness Consideration

To go beyond the application of warrants that are specified explicitly, it would be of interest to calculate reduction in delay caused by climbing lanes. In the present illustrative examples, safety impacts are not estimated.

Delay to vehicles attributable to operations on grade can be estimated with and without the climbing lanes. "Delay" is defined as the difference in travel time experienced by vehicles traversing the upgrade at the existing speed and the travel time which would be experienced if they were able to travel without constraint from slow moving vehicles [5, 23]. Here, the approach speed is assumed to be 90 km/h. Also, the reduction in delay attributable to the climbing lane is estimated.

In order to study the cost effectiveness of climbing lanes, rough estimates of costs have to be made. On the basis of cost of climbing lanes estimated for 1977 and the use of average yearly inflation of 5%, the average cost of providing a climbing lane is estimated to be $396,000/km in 1989 dollars (ignoring maintenance costs). Cost estimates are based on information obtained from MTO sources. In the constant dollars of 198[illegible] and assuming a 30 year time period, the cost of providing a climbing lane is $9570/year.

The cost effectiveness of climbing lanes can now be displayed in the form of delay reduction against cost obtainable from the climbing lanes under the various conditions of overtaking and traffic level. The methodology of cost-effectiveness is explained in reference 24. Figure 6.4 shows the results. Site 2 (which is hilly with a 7% grade) dominates Site 1 (rolling, 2.6% average grade) in cost effectiveness terms. For each site, cost effectiveness is much higher for those cases where, without a climbing lane, overtaking is not allowed, than where overtaking is permitted. The cost effectiveness of climbing lane improves with increasing traffic.

Economic efficiency of climbing lanes can be investigated from a comparison of benefits (i.e., savings of time converted into dollars) and costs. Benefits of providing climbing lanes include savings of time, improved level of service in general, and reduction of accidents.

Considering that travel time savings attributable to climbing lanes have already been estimated, dollar benefits to road users arising from travel time savings can be calculated. Assigning a $5/h of value time (in constant dollars of 1989) results in yearly savings. By combining benefit and cost estimates, we are in a position to estimate net savings per year for various DHV levels. Figure 6.5 shows the results.

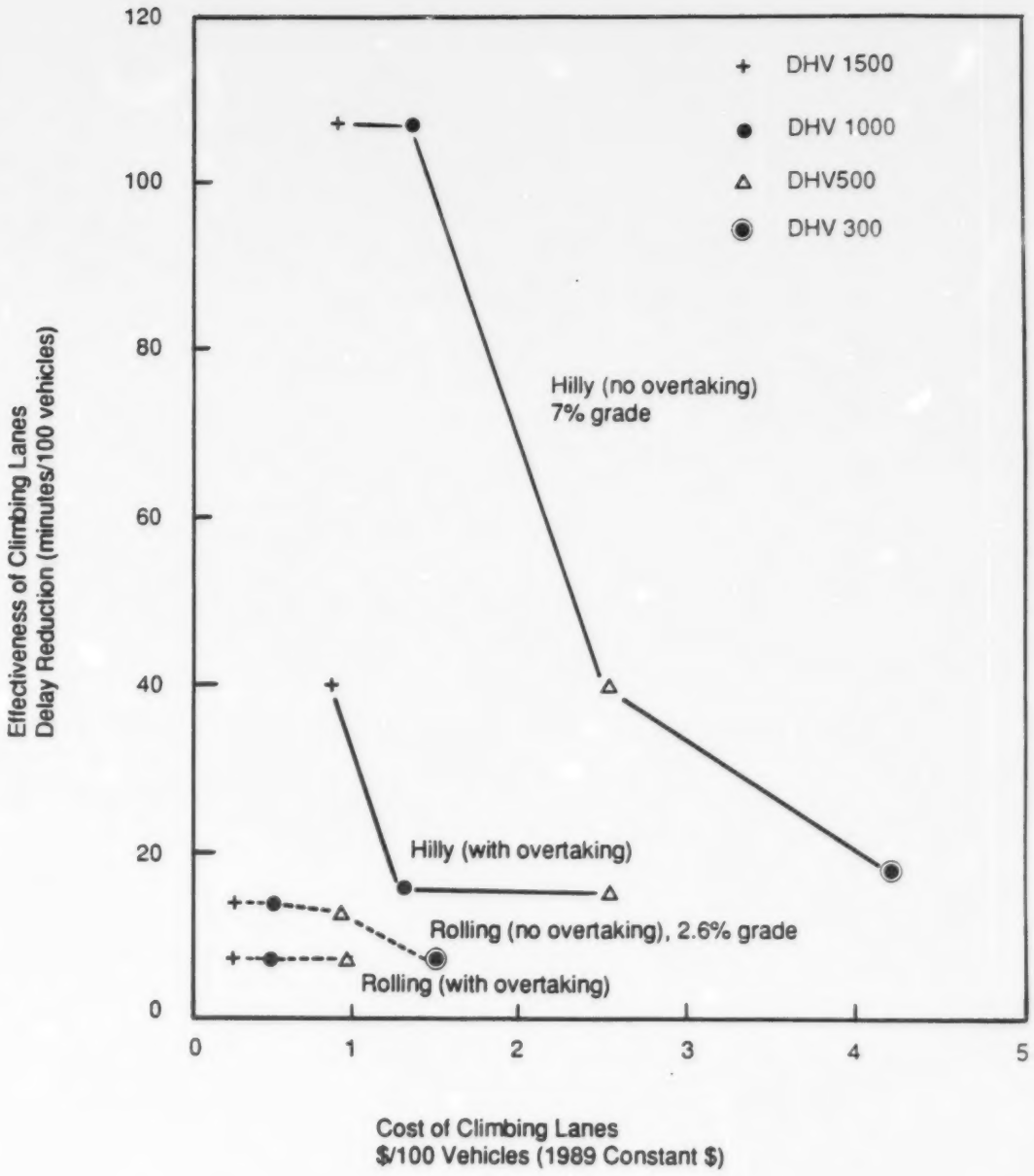

Figure 6.4: Cost-Effectiveness of Climbing Lanes
(For Illustration Purposes)

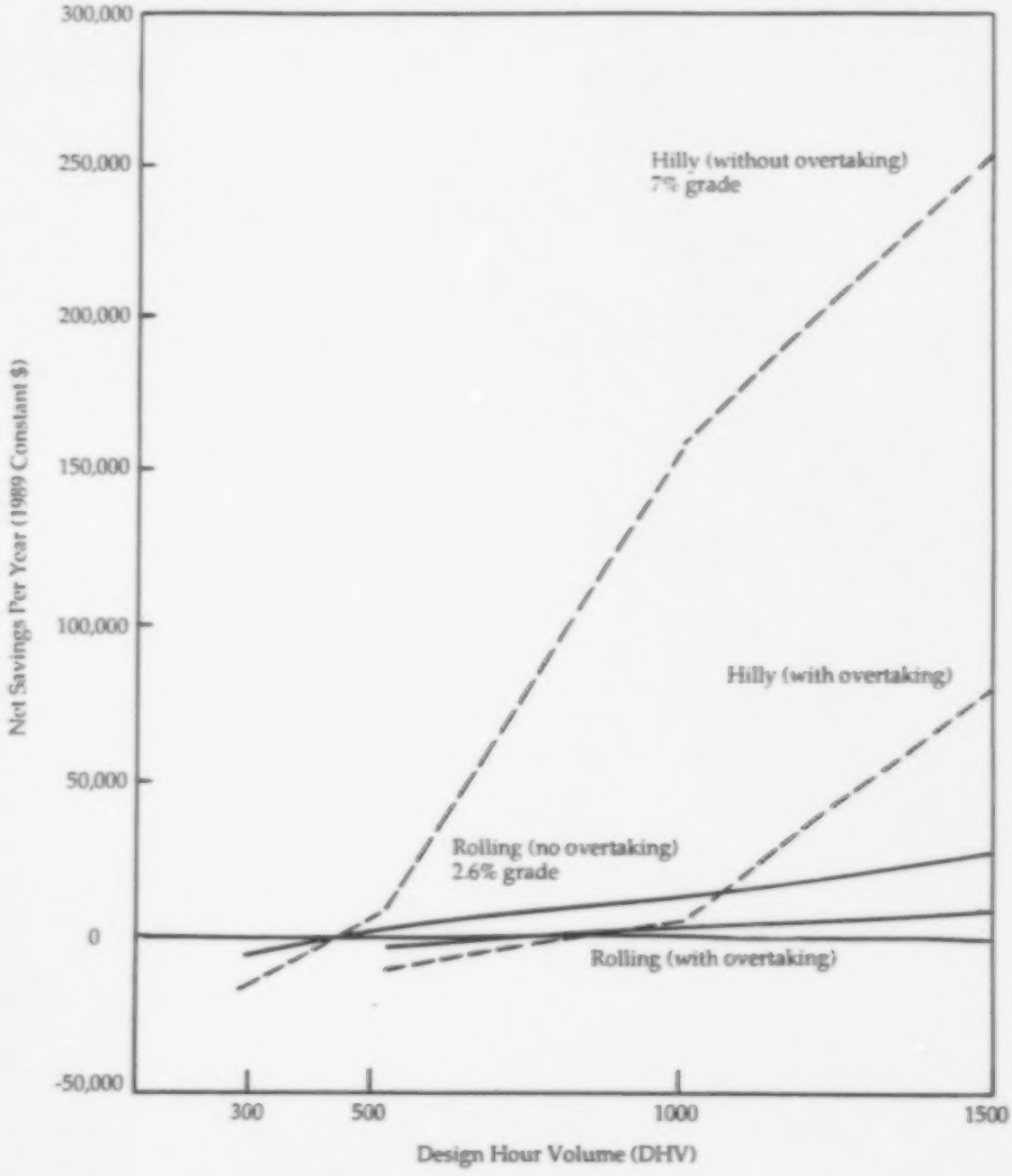

Figure 6.5: Economic Efficiency of Climbing Lanes
(For Illustration Purposes)

On the basis of the information presented in Figure 6.5, the following observations can be offered on the economics of climbing lanes:

- As expected, net savings due to climbing lanes increase with increasing DHV,
- Net savings are higher for the condition of "no overtaking" as compared to the case of "overtaking",
- On the basis of delay reduction alone, the economic feasibility of providing climbing lane is rather marginal for DHVs of up to 300 vehicles per hour,
- Addition of safety and other benefits may improve the cost effectiveness of climbing lanes for DHVs below 300 vehicles per hour.

6.6 Recommended Practice and Further Research

The review of warrants suggests that:

- the 15 km/h speed drop criterion should be maintained,
- the level of service drop of one or more levels should be used as a volume measure,
- on the basis of past research and guidelines offered by AASHTO, the climbing lane could start where a loaded vehicle represented by 180 kg/kw (300 lbs/hp) (for general application) experiences a speed drop of 15 km/h or higher,*
- the climbing lane could end where the design vehicle reaches a speed which is within 15 km/h of the operating speed of the highway,*
- the minimum length of a climbing lane should be 1.5 km, including tapers that are to be provided at entrance and exit of the climbing lane,
- final decision on the climbing lane provision and its length should be based on a cost-effectiveness basis.*

The cost-effectiveness consideration has been promoted by all agencies concerned with highway planning and design. For example, AASHTO states in the case of two lane roads that it is desirable to build a climbing lane where the critical length is exceeded -- provided the volume of traffic and trucks justify the added cost" [4]. It is also stated in AASHTO Design Manual that on highways with low volumes, climbing lanes although desirable, may not be economically justified even at sites where critical length of grade is exceeded [4].

There is some confusion on the level of service consideration. It appears that the TRB's suggestion (although not a governing case) of the LOS E or F is too restrictive for rural highways [5]. Even the AASHTO's capacity consideration, namely

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* Phase II of this research will provide further recommendations on design guidelines as well as cost-effectiveness technique.

LOS D for design year, would be restrictive. However, AASHTO also states that level of service drop could be one level poorer than desired (i.e., level of service C as compared to the desired LOS of B for the rural segments of a two lane highway). This warrant is consistent with the expectation of users who may tolerate low operating conditions on individual steep grades but not over long sections of highways [4].

The implications of the example applications presented in this chapter, and of the above observations, is that it would be desirable to assess the cost effectiveness of climbing lane alternatives and that the feasibility of individual cases should be checked as well. Development of methodology for feasibility and cost-effectiveness studies is recommended as a further extension to this research. Such techniques could be implemented in the form of a user friendly computer program.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The study of representative heavy vehicles and the uncertainty of existing MTO and other speed-distance curves in characterizing their performance on grade suggested the need to develop and test new curves. Two models were developed and used to generate speed-distance curves required for estimating heavy vehicle performance on grade. Model I (based on detailed simulation of vehicle motion), has the capability to treat different types of truck and selected recreational vehicle. It is viewed mainly as a research tool; its output is used to check Model II results. Model II, based on the SAE recommended procedures and empirical functions, can simulate a generic truck and recreational vehicle.

The output of both models in the case of truck compare reasonably well with field data. Model II output is somewhat compressed for the extreme values of entry speed and weight/power ratios. On the other hand, Model I output shows sensitivity to such extreme input values. Such a difference between models is logical given the detailed structure of Model I as compared to the aggregate nature of Model II.

In the case of recreational vehicles, performance based on both models is an overestimate of actual over the road performance for grades of up to 4 percent because drivers do not utilize engine power to the extent assumed by the model input. Compared to professional truck drivers, who are known to use engine power to a very high degree, private motorists are believed to trade off speed for engine power utilization (i.e., they tend to reduce speed rather than use full engine power). For grades of 6 percent or higher, the recreational vehicle drivers appear to use almost full engine power.

The gear change delay feature of Model I is not used for the production of speed-distance curves since discontinuities would require smoothing of the function. Also, the difference in speed with and without the gear change delay feature is not appreciable. Furthermore, there is lack of reliable data on driver behaviour in terms of gear change on steep grades.

In the case of vehicle loading levels of 180 kw/kg or higher weight/power ratio, the vehicle is not able to achieve the

maximum speeds of 100 km/h even on level grade. In such cases, the outputs included in Appendices A and B indicate the highest speed attainable by vehicles on zero grade. The significance of this observation is that in the case of rural highways with design speeds of 100 km/h, it would be inappropriate to assume that heavy trucks (of 180 or higher kg/kw ratio) would enter grades at the same speed as passenger cars and recreational vehicles.

The vehicles used for simulation are believed to be representative of their respective fleets. The weight/power ratios used cover a wide range of loading levels -- reflecting very light loading levels to very heavy loading levels. The 60 kg/kw is a light load condition, whereas the 100 kg/kw represents the average or typical truck (corresponding to the 50th percentile speed for trucks). The 180 kg/kw corresponds to a heavy truck -- representing the 12.5 percentile truck speed. A very heavy truck, such as the type used for transporting forest or farm products, can be assumed to correspond to a kg/kw of 210.

As a qualifier to the above observations, it should be recognized that data on the weight/power ratio are very scarce and that the recommended values for representative vehicles and loading levels are the best estimates that could be made. The data used to develop frequency distributions of gross weight/installed power ratios are believed to be representative of truck fleets at present. For the future, although there is a concern that the new weights and dimensions regulations would tend to increase weight to power ratio of loaded vehicles, the pressure to maintain highway speed may counterbalance this tendency.

Warrants used by various agencies for the provision of climbing lanes show similarities as well as differences. The MTO warrants that relate to critical length of grade (i.e., truck speed drop of 15 km/h) and the level of service drop on grade (as compared to the approach part of the highway) are not very restrictive. However, a cost-effectiveness type of assessment as a further evaluation step is desirable.

Preliminary tests carried out on the design of climbing lanes through the use of a microscopic simulation model, namely the TWOPAS model developed for the Federal Highway Administration (U.S.A.), suggest that the operational effectiveness of a climbing lane improves if introduced beyond the entry to the grade, preferably at the location where heavy vehicle speed drops considerably below the desired speed of traffic.

Example applications of speed-distance curves and a check on the fulfilment of warrants suggests that the justification of a climbing lane and its length is affected by terrain

(i.e., grade and length of grade), the choice of the design vehicle, the design hour volume (DHV), and the extent of passing allowed on grade sections of the highway. For a given design vehicle or a combination of vehicles, the cost-effectiveness and the economic efficiency of climbing lanes improve with increasing grade, increasing DHV and restrictions on overtaking slow moving vehicles prior to the provision of a climbing lane.

The inclusion of economic factors in the climbing lane warrants, in the form of cost-effectiveness criteria, would require the development of methodology for this purpose. The examples included in this report are illustrations of the type of analyses that would be required. A computer-based methodology for cost-effectiveness evaluations is not available at this time.

7.2 Recommendations

1. The representative heavy truck weight-to-power ratio should be changed from 200 kg/kw to 180 kg/kw for most regions and routes in Ontario. Only in cases where a significant proportion of commercial vehicles is of the type that can be considered to be very heavily loaded (e.g., those vehicles that carry forest and agriculture products), the use of higher ratios of kg/kw would be appropriate. Regional differences may require the use of 120 kg/kw, 180 kg/kw and 210 kg/kw ratios as representative vehicles. Should the estimated distribution of commercial vehicles be known for a given route, weighted average critical length of grade can be found from the speed-distance curves for weight-to-power ratios of 120 to 210 kg/kw.

2. The results of Model II should be adopted for planning and design of climbing lanes. The reasons for such a recommendation are as follows:
   - Model II is based on the Society of Automotive Engineers recommended procedures and empirical functions for estimating vehicle performance on grade,
   - Model II outputs are easier to use (as compared to Model I) since a single curve can be used for all types of truck. Thus, it would not be necessary to estimate commercial vehicle profile (i.e., proportion of various types of truck).

3. For increased safety and avoiding unreasonable delays caused by heavy vehicle performance on grade, the normal speed reduction criterion for climbing lane consideration should be kept at 15 km/h.

4. Entry speeds used for the estimation of critical length of grade should reflect the nature of highway and design speed.

For most two lane rural highways, 90 km/h would be appropriate.

5. On routes where recreational vehicles dominate the slow moving vehicle population and truck population in the traffic is negligible, the recreational vehicle performance should be used as a basis for estimating critical length of grade. A representative recreational vehicle should correspond to a weight/power ratio of 40 kg/kw. Output of model II should be used for this purpose. However, by way of a note of caution, it should be recognized that for grades less than 5%, the model results overestimate speed of such vehicles on grade. Reasons for such a discrepancy are given in the report.

6. The level of service criterion for the provision of climbing lanes should be retained for use by the MTO. That is, whenever, there is a drop of one or more levels of service upgrade (e.g., level of Service C upgrade vs. B at the approach), a climbing lane should be considered for that site.

7. An additional criterion that would be desirable for inclusion in the list of warrants is the cost-effectiveness of climbing lanes. The MTO warrants now treat the economic justification in an informal fashion. For comparison of the effectiveness of alternatives for a given site, as well as for relative merits of climbing lanes to be provided at different sites, such a criterion would ensure the best use of funds.

8. Further research should be carried out to develop cost-effectiveness methodology for the evaluation of climbing lanes. Additionally, such a methodology should be implemented as a computer program for the estimation of cost-effectiveness of climbing lanes.

9. The design of climbing lanes should continue the practice of starting such lanes where the speed of heavy vehicle drops below 15 km/h of the prevailing highway speed and ending it where the heavy vehicles regain speed to the extent that the speed differential is not higher than 15 km/h. Trade-offs between length (and therefore cost) of climbing lane and effectivness can be made through the use of cost-effectiveness methodology.

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